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MATERIALS HANDLING FOR URBAN TUNNELING IN ROCK

J. M. Duncan
L. A. Giamboni
H. V. Schneider
P. E. Sperry

Holmes & Narver, Inc.
999 Town & Country Road
Orange, California 92668

MAY 1979

FINAL REPORT

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16. Abstract

An examination of prior forecasts of tunnel construction provides an estimate of 2.4 million feet of rock tunnel to be constructed during the 1976-2000 period. Tunnel projects for the near term (1980+) and far term (1990+) periods are defined for study. The flow and characteristics of materials handled are defined for the tunnel projects. The state of the art and status of R&D programs for materials handling are reviewed. Based on extensive interviews with representatives of tunnel contractors, equipment manufacturers, government agencies, and consultants, the application of various methods of material handling to tunneling is discussed, including conventional rail haulage, crane and hoist lifting, and horizontal transport and lifting by hydraulic and pneumatic pipeline and by conveyor. Total job cost estimates using these modes of material transport are obtained (with material handling costs isolated) by modification of an estimating technique used for preparing contractor bid estimates. A comparison of the results indicates that major cost savings through substitution of alternative material handling modes should not be anticipated. R&D program elements are recommended to assure that material transport will not become the limiting factor as the rate of tunnel excavation increases in future years.

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PREFACE

This study was sponsored by the Office of Rail and Construction Technology, Office of Technology Development and Deployment of the Urban Mass Transportation Administration of the U.S. Department of Transportation. The effort was conducted under contract with the Transportation Systems Center for the Urban Rail Construction Technology Program.

The authors wish to thank Sam Gozzo, Bruce Bosserman, Allen Chin, and Jim Lamond of the Transportation Systems Center for their many helpful comments and constructive criticism, for review of the early manuscript, and for patience during the course of the project.

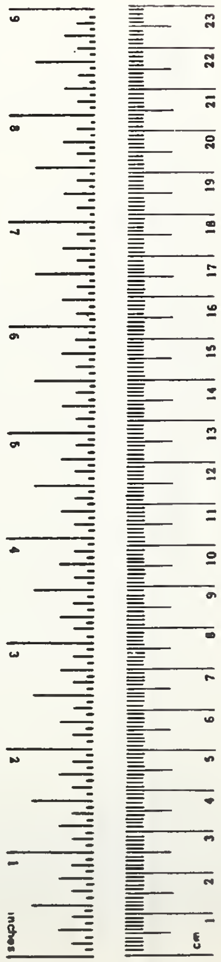
This study is directed to the interest of professionals in tunnel construction. Extensive use was made of personal contacts with many people in contractor, equipment manufacturer, and supporting organizations. Special recognition for their contributions is due to the individuals listed in Appendix C who gave generously of their time for candid discussions of their experiences and thoughts regarding materials handling for tunneling.

P.E. Sperry and H.V. Schneider, co-authors of this report, are consultants in tunneling and materials handling, respectively.

METRIC CONVERSION FACTORS

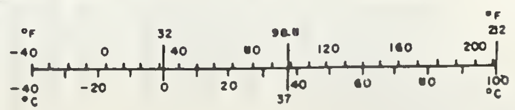
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.5	kilometers	km
		AREA		
in^2	square inches	6.5	squsre centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inchss	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square ysrds	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10.000 m^2)	2.5	scres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fshrenheit temperature	°F



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EXECUTIVE SUMMARY

MATERIALS HANDLING FOR URBAN TUNNELING IN ROCK

Principal Investigator: James M. Duncan
Holmes & Narver, Inc.
999 Town & Country Road
Orange, CA 92668

Sponsor: Urban Mass Transportation Administration

Effective Date of Contract: January 7, 1977

Duration of Contract: 21 months

Objective: The objective of this study is to assess the potential for achieving construction cost economies in tunnel construction through selection of more efficient materials handling systems and/or further development of system components, and to identify elements of an R&D program with potential for benefical research to assure adequate material transport capability as the rate of heading advance increases.

Scope of Study: An examination of prior forecasts of tunnel construction provides an estimate of 2.4 million feet of rock tunnel to be constructed during the 1976-2000 period. Tunnel construction projects for the near term (1980+) and far term (1900+) periods are defined for study. These projects are limited to those anticipated for urban mass transit systems, constructed in rock by use of tunnel boring machines. The tunnel projects selected for major emphasis have twin 20-foot excavated tubes of circular cross section as this is the principal configuration for transit tunnels being built in the United States.
Other characteristics are:

	Near Term	Far Term
Average advance rate, ft/dy	120	300
Maximum advance rate, ft/dy	240	600
Tunnel length per job, ft	20,000	80,000
Tunnel length per reach, ft	10,000	40,000
Tunnel grade, percent	± 4	± 10
Minimum radius curve, ft	250	750
Shaft depth, ft	100	200

The impact of variations on these configuration parameters were investigated but in less detail than for the principal configurations The flow and characteristics of materials handled were defined for the tunnel projects.

Material handling systems were considered for both horizontal and vertical transport of incoming and outgoing materials. The transport modes include:

Horizontal	Vertical
Rail	
Rubber Tire (incoming only)	
Conveyor	Conveyor
Pneumatic	Pneumatic
Hydraulic	Hydraulic
	Bucket Elevator
	Hoist
	Crane

Various combinations of the horizontal and vertical modes were investigated. Four conveyor configurations suitable for lifting were included.

The study consists of three major parts: (1) surveys of the state-of-the-art of materials handling in tunneling, of material handling systems which might be applicable to tunnel construction, and of the status of R&D programs for materials handling; (2) development of a cost estimating model based on an estimating technique used for preparing contractor bid estimates, and determination of comparable costs for tunnel construction projects (with material handling costs isolated) using various material handling systems; and (3) recommendation of an R&D program based on anticipated benefits and development costs of potential R&D projects.

The investigation included extensive interviews with representatives of tunnel contractors, equipment manufacturers, government agencies and consultants.

Research Justification: As the competition for surface space in urban areas becomes greater and the antagonism to aesthetic and noise degradation of the environment mounts, more attention is given to subsurface as a logical location for transit systems. The high cost of providing underground space impedes the decision to go underground. As one of the three major elements of the tunneling process, materials handling contributes significantly to this cost and can become the limiting factor in tunnel face advance rate as improvements are made in the technologies of

excavation and ground support. It is, therefore, prudent to investigate alternative possibilities for material handling systems and to identify areas for beneficial development to reduce the cost of materials handling and to prevent the handling of materials from becoming an impediment to reduction of tunnel construction cost through increased rates of face advance.

Summary of Results: A comparison of the results obtained from detailed cost estimates for tunnel construction total project costs using various modes of horizontal and vertical materials transport indicates that major cost savings through substitution of alternative material transport methods should not be anticipated. The lifting of materials from the tunnel to the surface appears to present more difficulty than horizontal transport, and it will become a constraining factor before the horizontal transport system becomes saturated.

The basic technology of the conventional haulage systems (rail, crane, hoist) used for underground transport appears to be adequate for near term requirements although improvement is needed in design, installation, operation, and maintenance of the systems to obtain full advantage of the basic capabilities. As advance rates increase more attention will need to be given to total system investigation and to extension of the horizontal transport system.

The technology of rubber-tire vehicles for underground haulage appears to be adequate to provide a basis for development of a specialized vehicle for palletized transport of incoming materials in support of continuous methods of muck transport.

The application of belt conveyors for transport of muck from the heading to the shaft or portal during tunnel construction presents a set of requirements different from those for overland conveying, face haulage of coal or mainline haulage of mined materials. Most of these requirements are less severe than their counterpart found in other applications. It should, therefore, be possible to accommodate these requirements applying (in less costly concepts) the principles used to meet the more severe requirements of other applications. If this approach can be used successfully to solve the principal problems of system extension and operation around long radius curves, the application of a conveyor system for muck haulage in tunnel construction will be an alternative open to the contractor based on his preference and assessment of economic competitiveness.

Bucket elevators have difficulty releasing wet, sticky materials encountered in tunnel muck. They also are height-capacity limited for a single flight by current commercial conditions to something less than that projected for the far term case. Conventional inclined belt conveyors require excavation of long auxiliary inclined tunnels. Special convoluted belt designs are expensive. A conveyor belt configuration based on the cover belt principle appears to overcome most of these problems although its ability to achieve the far term height-capacity requirement has not been demonstrated.

Although slurry transport systems are widely accepted for continuous transport of large volumes of small particle size bulk materials over long distances with relatively steady feed rates, much work remains to be done to develop the engineering data needed for design of systems to transport reliably materials with large and variable particle size under conditions of variable feed rate. Favorable economics of slurry transport under these conditions for short term installations with relatively small volumes and short distance have not been demonstrated. Low cost methods for separation of fines from the slurry, typical of a wide range of rock tunnel muck remain to be developed. Several programs are under way or planned to continue the investigation of slurry transport.

Pneumatic transport of bulk materials has been demonstrated to be practical and economically competitive for specific applications such as transport of low density or finely divided materials, backfill stowing, and hoisting of coal in specific situations. The high velocities required to suspend large, dense particles accelerate pipe wear and cause high power consumption. Transport of large, dense particles in the tonnage range projected from the far term period has not been demonstrated. The problems caused by sticky materials encountered in many tunnels (including rock) have not been investigated.

The cost estimating model developed for the study consists of a modification of a professional construction cost estimators standard method for estimating construction tenders for tunnel bid solicitations. The estimating procedure has been computerized to reduce the time required for consideration of alternative material handling systems and components, and to improve mathematical accuracy.

Fifty-five problems for potential R&D program elements are identified. The program gives major emphasis to lifting muck by continuous mechanical methods and to horizontal transport of muck by upgraded rail haulage. The full potential of intermittent hoisting should be developed, particularly for the intermediate term (4 to 10 years). Investigation of belt conveyors based on recently developed belt technology is recommended as a backup system to rail haulage. Monitoring and assessement of the results from ongoing development programs for pipeline systems are recommended and better definition of the feed and discharge end problems for transport of tunnel muck should be developed.

1. INTRODUCTION

This effort was undertaken for the Transportation Systems Center on behalf of the Urban Mass Transportation Administration's Office of Rail and Construction Technology. The goal of the construction program is to effect a significant reduction in the cost of rail transit system facilities construction by implementing innovative technology for improved performance and life cycle cost and by improving design, construction and contracting practices in the urban rail construction industry.

The urgent need for significant reduction in construction cost, if subways are to be a viable mode of transportation in the future, has been of concern for many years. A recent paper (16)* identified four key ways to lower subway construction costs:

a. More carefully study alternatives in the planning phases.

b. Introduce new technology.

c. Reduce the burden of risk associated with the introduction of new technology.

d. Establish better contracting practices.

As an example of the benefits to be gained by using different technology, an apparent saving of 11 million dollars is indicated for the Peachtree Street subway in Atlanta by switching to conventional rock tunneling rather than the cut and cover construction which had been planned.

In 1969 a study (21) was funded by the U.S. Department of Transportation (DOT) to investigate the potential for innovations in materials handling systems for construction of extremely long (20 to 450 miles) tunnels in rock for deep underground transportation systems which were visualized for the long term future. In order to evaluate the suitability of alternative methods of material handling and to identify the severity of material handling problems anticipated for these projects, rates of excavation and other project parameters were selected in ranges far beyond those of today's technology. For example, excavation advance rates were 300 to 750 feet per average day and up to 1500 feet per peak day, tunnel depths from 500 to 3500 feet, and shaft spacing from 5 to 20 miles.

The present study evaluates material handling systems applied to modern (present day and near future) tunneling technology in the urban environment where tunnel depths are less than 200 feet and average advance rates are anticipated to be in the order of 50 to 300 feet per day.

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*Numbers in parentheses indicate references listed in Appendix A.

MASS TRANSIT SYSTEM

A typical urban mass transit system is shown in Figure 1. It consists of several lines of travel by a dual fixed-guideway system consisting of steel-wheeled vehicles running on steel rails. The routes usually follow the most heavily developed corridors fanning out from the central business district (CBD) and terminate at specific points such as airports or where the population density decreases beyond justification for a mass transit system. Segments of the routes are constructed as subway, at-grade, or aerial structures as determined by least cost or by compromise between cost and impact on the environment.

Stations for loading and unloading of passengers are placed along routes at convenient intervals which may vary from several hundred feet in the CBD, where real estate and construction costs are highest, to a few miles in outlying areas of low population density. Based on data provided by Vaccaro (85), the average distance between stations for future urban transit systems will be about 4000 feet. The stations also are subsurface, at-grade, or aerial, to correspond to the guideway elevation.

Construction is generally subsurface in heavily developed areas of the CBD and suburban commercial centers where real estate values and construction costs are highest. As routes extend from the CBDs, they eventually surface because population density, land values, and available space make surface alternatives less costly. In some instances, however, environmental concerns, surface disruptions, and related political influences swing the balance away from the least cost, at-grade alternative.

TUNNELING DEMAND

A survey (85) of fixed guideway urban transit systems existing or planned for the United States in the 1976-1990 time frame was conducted for the DOT. Although the survey indicates a high degree of uncertainty in the plans for urban transit systems, the results may be summarized roughly as follows and in Table 1.

a.	Existing transit route miles, surface and subsurface (part of current operating systems)	487
b.	Future transit route miles, surface and subsurface (under construction and planned)	1125
c.	Future transit route miles, subsurface (under construction and planned)	272
d.	Future stations (subsurface)	155

The future subsurface transit route miles total (item c) is heavily influenced by construction now in progress in Washington, D.C. (48 miles, 17 percent of total) and moth-balled due to lack of funding in New York City (137 miles, 50 percent of total). The current subsurface route miles of construction (Table 1) also are dominated by the 137 miles of construction

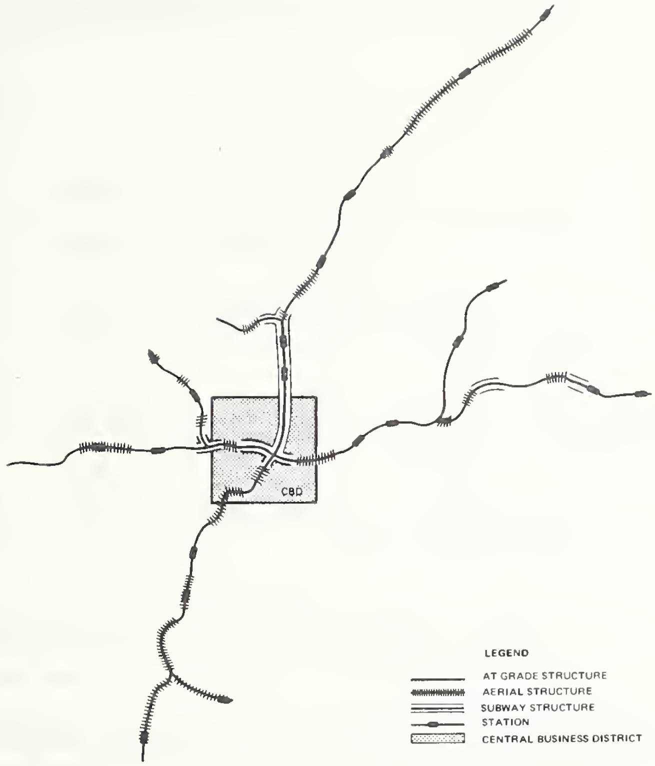

FIGURE 1. TYPICAL URBAN MASS TRANSIT SYSTEM

in New York City, which is all cut and cover. In deriving the summary figures of Table 1, arbitrary assignments, influenced by the geological information presented by Cushing and Barker (13), were made to the various types of construction for the undesignated but specified route miles of future subsurface construction.

A comparison of costs for subsurface route construction given by Vaccaro (85) reveals higher costs per double-track mile for cut and cover construction than for tunneling in rock. For Washington, D.C., costs for conventional tunneling in rock or soft ground are about the same ($18.5 million per route mile) as for cut and cover in suburban areas. However, the cost for cut and cover in the CBD is about 70 percent higher ($31 million per route mile) and for tunneling in rock using a tunnel boring machine (TBM), about 30 percent lower ($13 million per route mile).

As suburban population densities continue to increase, causing reduced availability of land and increased right-of-way costs, and as concern for adverse impacts on the environment intensifies, a trend toward larger portions of urban mass transit system construction being underground can be anticipated, particularly if reductions in the relative cost of subsurface construction can be achieved.

TABLE 1. SUBSURFACE CONSTRUCTION TO 1990

Type of Construction	Route Miles			Percent of Total	
	Current	Future	Total	Current	Future
Tunneling in rock	18.4	23.5	41.9	10	30
Tunneling in soft ground	15.2	8.5	23.7	8	11
Cut and cover	158.7	45.8	204.5	82	59
TOTAL	192.3	77.8	207.1	100	100

A shift in the relative amounts of the various types of subsurface construction also may be anticipated when it is observed that:

a. Cut and cover is the most disruptive and environmentally damaging method used, and this is not likely to improve.

b. Cut and cover construction requires the handling of up to five times as much material (excavation and backfill) as that removed from the tunnel space.

c. Cut and cover is usually restricted to routes which are under streets or other public right-of-way.

d. Underpinning to protect structures adjacent to cut and cover construction is a major cost.

e. Cut and cover must be at shallow depths to be economical, thus eliminating the possibility of deep subway routes independent of street routes.

f. Costs for tunneling in rock have decreased with the introduction of new technology such as the TBM, while costs for cut and cover have increased due to environmental restrictions.

g. Rapid installation of low cost primary ground support and reduction of delays caused by ground water must be achieved before significant reduction in the cost of soft ground tunneling can be expected.

h. Improvements are being made in TBM technology resulting in more rapid penetration rates, greater reliability, and more flexibility for application to a variety of rock conditions.

These considerations and political pressures may shift underground route construction from primarily cut and cover toward deep rock tunneling of subway systems.

If assumptions are made that:

a. Four hundred route miles (40 miles per year from 1990 to 2000) of additional urban transit system will be planned by the year 2000;

b. The portion of route miles constructed underground will be 1.2 times as great (29 percent of total) as found to be under construction and planned in the survey (85);

c. The portion of subsurface construction in rock will be 1.2 times as great (36 percent of total) as found in present plans;

d. The portion of subsurface construction in soft ground remains about the same as in present plans;

then a projection for future subsurface construction plans to the year 2000 can be made as indicated in Table 2.

Since subways built by tunneling in soft ground or rock are usually placed in dual tubes while cut-and-cover-constructed tunnels contain two-way traffic, the tunnel feet of future subsurface construction to the year 2000 would be as shown in Table 3.

TABLE 2. FUTURE TRANSIT SUBSURFACE CONSTRUCTION IN ROUTE MILES

Time Period	Route Miles			
	Total	Rock	Soft Ground	Cut and Cover
To 1990	77	23	8	46
1990 to 2000	116	42	13	61
Total to 2000	193	65	21	107
Percent of total miles		34	11	55

This represents an average of about 59,000 tunnel feet per year over the 25-year period from 1976 to 2000.

Another estimate of the demand for tunnels in the United States, made by Mayo, Barrett and Jenny in 1975 (52), looked at the historical and future demand for the period 1955 through 1985. Tunnels which are included in various plans, but are unlikely to be built or under construction by

TABLE 3. FUTURE TRANSIT SUBSURFACE CONSTRUCTION IN TUNNEL FEET

Type of Construction	Tunnel Feet	Percent
In rock	687,000	47
In soft ground	222,000	15
By cut and cover	565,000	38
TOTAL	1,474,000	100

1985, are not included in the data presented. The summary data derived from their extensive questionnaires and interviews with staff members of financing, grant, and owner-operator agencies are presented in Table 4. The "other" tunnel use includes railroad tunnels and cooling water supply and discharge tunnels for major electric power plants such as the nuclear power plant at Seabrook, New Hampshire.

The detailed analysis of data presented by Mayo et al (52) as level-of-construction activity of each major tunnel use shows sharp peaks for rapid transit tunneling (including cut and cover) in the periods 1965-1970 (50,000 ft/yr) and 1975-1980 (75,000 ft/yr). In the other 5-year periods the construction activity drops to very low values. However, the level of both the peaks and valleys increases continuously during the 30-year period

TABLE 4. TUNNEL CONSTRUCTION DEMAND IN U.S.

	Linear Feet of Tunnel			
Tunnel Use	1955-65 (Actual)	1965-75 (Actual)	1975-85 (Estimated)	1975-85 (Average/ Year)
Rapid transit	2,900	211,200	346,000	34,600
Water and sewer	902,900	1,108,300	696,700	69,700
Motor vehicle	46,700	28,200	51,195	5,100
Other	15,700	0	34,900	3,500
TOTAL	968,200	1,347,700	1,128,795	112,900

Source: Cresheim Survey, 1975 (52)

of the survey. This cyclical trend might be anticipated to continue to the year 2000. The 10-year average (1975-1985) for rapid transit tunneling (34,600 ft/yr) may be low for planning purposes since it does not include tunnels already in agency plans if they are not likely to be under construction by 1985, and there is no consideration of the possibility of increased portions of rapid transit systems being underground due to social pressures and improved economic competitiveness.

The detailed analysis for water and sewer tunneling (no cut and cover included) shows a continual buildup of construction activity from 1955 to 1968 when a peak of about 190,000 tunnel feet per year was reached. Since 1968 the trend has been downward to an average of about 70,000 tunnel feet per year in the 1975-1985 period. Since no tunneling activity by the California Department of Water Resources or the Metropolitan Water District was included in the projections for the 1975-1985 period, a long term projection at a rate greater than that (48,000 ft/yr) derived from current data for the 1975-1985 period may be warranted. A value of 65,000 tunnel feet per year may be reasonable.

The analysis for motor vehicle tunneling (no cut and cover included) shows a peak of nearly 12,000 tunnel feet per year during the 1960-1965 period, but decreasing activity to an average of about 5000 feet per year for the 1975-1985 period. An increase in motor vehicle tunneling activity is not anticipated unless highways under cities are adopted in lieu of beltways.

Other tunneling (railroad and power plant) is difficult to project due to lack of an adequate data base. If three power plant cooling systems equivalent to Seabrook and no additional railroad tunnels are assumed during the 1985-2000 period, a total of 90,000 tunnel feet would be built.

An estimate of total tunnel demand in the United States to the year 2000 can now be developed using data for rapid transit tunnels from Table 3 and data based on Table 4 for water, sewer, motor vehicle and other tunnels. The results of this projection are shown in Table 5.

TUNNEL CONSTRUCTION METHODS

The most common construction method for present-day underground rapid transit system tunnels is cut and cover. Over 80 percent of the current subsurface transit system route miles are constructed by this method. O'Neil et al (61) briefly outline this method of construction. It is a multi-step procedure in which the contractor diverts traffic and utilities, constructs an excavation support system, excavates the tunnel space (usually rectangular in section), erects the cover, backfills, and restores utilities and surface features. Two variations of this technique are used. In one, the excavation is made by removing material from the top (open cut excavation) and then installing a cover to support the backfill material. In the other, (under-the-roof construction) side supports, a cover, and backfill are put in place before the material is excavated from the tunnel space. Excavation proceeds under the roof by appropriate soft ground methods. Open cut excavation is more common in the United States.

TABLE 5. TUNNEL DEMAND IN THE UNITED STATES, 1976-2000

Tunnel Use	Thousand Linear Feet of Tunnel			
	Total	Rock	Soft Ground	Cut and Cover
Rapid transit, 1976-2000	1,474	687	222	565
Water and sewer, 1976-1985	697	627	70	
Water and sewer, 1986-2000	975	877	98	
Motor vehicle, 1976-1985	51	51		
Motor vehicle, 1986-2000	75	75		
Other, 1976-1985	35	35		
Other, 1986-2000	90	90		
TOTAL	3,397	2,442	390	565

In the open cut method, materials handling is primarily lifting material to the surface, usually by mobile crane from depths less than 60 feet, and loading it onto large trucks for surface transport to a disposal or storage area. In the under-the-roof method, excavation of overburden down to the roof line is the same as in the open cut method, but excavation of the tunnel space is performed by digging at a moving vertical face within the confines of the tunnel side supports and the roof cover. The material is then transported horizontally to a point where it is lifted vertically from the tunnel invert to the surface (usually less than 60 feet) and loaded into trucks for disposal. Material handling during under-the-roof excavation is similar to soft ground tunneling but without the need for installation of ground support simultaneously with excavation, and the length of underground haulage is kept short by moving the lifting point ahead.

Rock and soft ground tunneling are both performed entirely underground by excavation of material from a constantly advancing vertical face. All material excavated and all materials required for installation of ground support must be transported horizontally through the tube formed by the excavation. Materials enter or leave the tunnel either through a shaft (vertical or inclined) or through a portal.

The high cost of underground construction dictates that tunnels be built of minimum size acceptable for the intended use. Continuous excavation methods, which provide the most rapid rates of face advance, generally

require a circular excavation section. This also is preferable for ground support. The high cost of surface work space in an urban area, considerations of the impact on the environment, and the cost of constructing access to the underground all require that underground access be minimized. Shaft access to urban tunnels is common practice because mass transit systems seldom surface in the CBD due to cost, aesthetic and environmental considerations. Political pressures require that public works projects such as tunnels, once started, be completed as quickly as possible to minimize disruptions to normal activity and to provide use of the new facility at the earliest possible time. Inflation adds tremendous impetus for both the owner and the contractor to finish the job as soon as possible.

These considerations require that tunnel construction be accomplished with interdependent, simultaneous operations proceeding as continuously as possible in a single confined space at the tunnel heading. All access to this small, congested space is usually through a vertical shaft and along a long, narrow tube. The forces that dictate these conditions will not change. For the advantages of the use of underground space to materialize, tunneling techniques that are compatible with these conditions must produce economical underground excavations.

EXCLUSIONS FROM ANALYSIS

The following types of tunnel construction, structural features associated with tunnel construction, and types of materials handling are excluded from the analysis in this study for the reasons indicated.

a. Cut and cover construction. Normal heavy construction material handling methods such as clamshell and crane are used. Except in very special cases, there is only slight possibility of improvement through research.

b. Sunken tube construction. Only a very small amount of this type construction is anticipated for mass transit systems. The techniques involved, including dredging of marine materials, mass concreting, and deep sea diving, are a completely different field from urban tunnel construction.

c. Pipe jacking construction. This technique is suitable for tunnels with diameters 10 feet or less in soft ground.

d. Highway tunnels. Only a very small amount is anticipated in urban locations.

e. Tunnel segments less than 500 feet. These short tunnels are usually highway or railroad underpasses with portal access where rubber tired vehicles are economical for material handling. Materials handling is not a limiting factor.

f. Mixed face tunneling. Material handling is not a limiting factor in the slow excavation progress that is possible with the condition of both soft ground and rock in the same face.

g. Station construction. Material handling is usually not a limiting factor in subsurface station construction due to drill and shoot excavation in small rounds to preserve the integrity of the remaining rock. The same short-haul material handling techniques are applicable as for short tunneling operations.

h. Shaft construction. Although muck handling techniques need improvement, the conditions are entirely different from tunneling. During shaft construction, material transport is vertical with a continually increasing height of lift from the receding horizontal excavation face, whereas in tunnel construction the major transport is horizontal from a continually advancing vertical face.

i. Miscellaneous structures. Numerous miscellaneous underground excavations, such as adits to connect vent shafts to the running tunnel, connections between running tunnels, pockets or rooms for power or pump stations and escalator ways are included in subway systems. These are not considered as the volume of these structures is relatively small and their construction is incidental to the main tunnel.

j. Utility extension. Current techniques appear to be adequate for the extension of the utility pipes and cables required for tunnel excavation at the advance rates anticipated.

k. Final lining subsequent to excavation. When a concrete lining is placed after the excavation is complete, no additional demands are made on the excavation material handling system except that it be compatible with the concrete delivery system. Since the final lining is constructed after excavation is complete, the material handling problems are not interrelated.

l. Positioning and installation of materials. The erection or positioning of ground support materials involves entirely different techniques than the transport of materials to and from the working zone. The analysis of these techniques should be the subject of separate investigation.

m. Packaging of materials. There is no apparent reason for delay of the tunnel advance due to unloading, unbundling, rearranging, packaging or loading of construction materials at the surface work yard.

n. Exotic excavation methods. Research and development have been conducted recently or are in progress on exotic excavation methods such as flame jet, laser beam, water jet, thermal probe (Subterrene) and continuous drill-and-shoot. It is doubtful that flame jets or laser beams will be developed to commercial application for medium to large size tunnels due to the large consumption of energy and heat removal problems. Full bore excavation with water jets also appears to be defeated by high power consumption and other problems. However, water jet assist for moles is considered by some observers

to have promise for future application. If this occurs, it should not have severe impact on the material handling system due to the relatively small amount of water used.

Advance rates of 15 to 20 feet per 8-hour shift in a 13-foot-diameter tunnel have been reported (58) for the use of hydraulic transport and water jets to cut very soft rock (St. Peter sandstone in Minneapolis-St. Paul). This is considered as a special case.

Another special situation being developed for excavation in soft granular soils bearing water is the bentonite tunneling machine (2). A bentonite slurry is pumped into a sealed chamber to provide ground support at the face. The resulting slurry containing the excavated muck is withdrawn from the chamber through valves and pumped to dewatering stations for muck disposal and recirculation of the water. The anticipated rates of advance are quite low due to the need for ground support installation behind the mole.

Although cost savings of 6 percent compared to current methods for excavation of a 20-foot tunnel are indicated for the Subterrene tunneling system (3), much development of equipment remains to be done before the method can be demonstrated on a commercial scale. If this method proves to be technically feasible and economically competitive, its commercial application appears to be many years in the future.

Another advance in excavation method is the continuous or spiral drill and blast concept (63, 64). Estimates for a 1-mile-long, 18-foot tunnel (based on 35 feet of 10-foot tunnel excavated) indicate cost reductions of approximately 50 percent and advance rates four times greater than conventional drill and blast methods. Commercial acceptance of this method may provide advance rates for drill and shoot excavation of short or noncircular tunnels in the same range as those presently achieved by tunnel boring machines. The muck produced by this method would have characteristics similar to those of muck from conventional drill and blast and would present no new requirements for the material handling system.

With the uncertainty of commercial acceptance of exotic excavation methods, it does not seem warranted to include their impact on material handling systems in the detailed analysis of this study. Therefore, the comparative analysis of material handling systems is confined to the requirements of conventional excavation methods.

2. THE TUNNEL PROJECT IN AN URBAN ENVIRONMENT

TUNNEL CONSTRUCTION

A tunnel construction project consists of a number of interrelated activities taking place simultaneously at the heading, at various locations along the tunnel access, and at the surface area adjacent to the tunnel access. The requirements and performance of tunnel construction have been described in considerable detail in several publications (4, 21, 51, 80).

Work Areas

Several distinct work areas can be identified for a typical tunnel project as indicated in Figure 2.

After access to the underground is gained by sinking a shaft or developing a portal excavation is continued at a vertical face which constantly or intermittently advances along the predetermined route of the tunnel. Initial ground support is installed, when required, immediately behind the face excavation. Extension of utilities and extension of the materials handling system occur as closely as possible behind the installation of ground support. The space in which these three functions (excavation, ground support installation, and utilities and material handling system extension) are performed is designated the "heading". Incoming materials handling activities taking place in the heading include unloading, moving and installation of ground support materials, pipe and cable for utility extension, and materials and/or equipment for extension of the material handling system. Outgoing materials handling activities include loading and/or processing of excavated material (muck) and other waste materials.

The primary activities in the tunnel space between the heading and the shaft or portal are horizontal transport of materials to and from the heading and maintenance of the material handling system. Occassionally other activities such as placement of grout, water removal, upgrading of the material handling system, and installation of tunnel lining occur in this zone.

The development area (Figure 2) is the space adjacent to the bottom of the shaft. This space is excavated by drill-and-shoot or other suitable methods to provide space for material storage, for assembly of the tunnel boring machine or excavation shield, for transfer of materials from the horizontal transport system to the vertical lift system and to provide access from the shaft to the tunnel in the case of an offset shaft. In some cases, maintenance of major equipment is also performed in this area. Typical dimensions of the development area are shown in Figure 2. In some cases, depending on the type of intermodal material transfer required, portions of the development area floor are excavated below the invert elevation.

The shaft, used for vertical access to the development area and tunnel, is excavated at the location of a station or subway ventilation shaft whenever

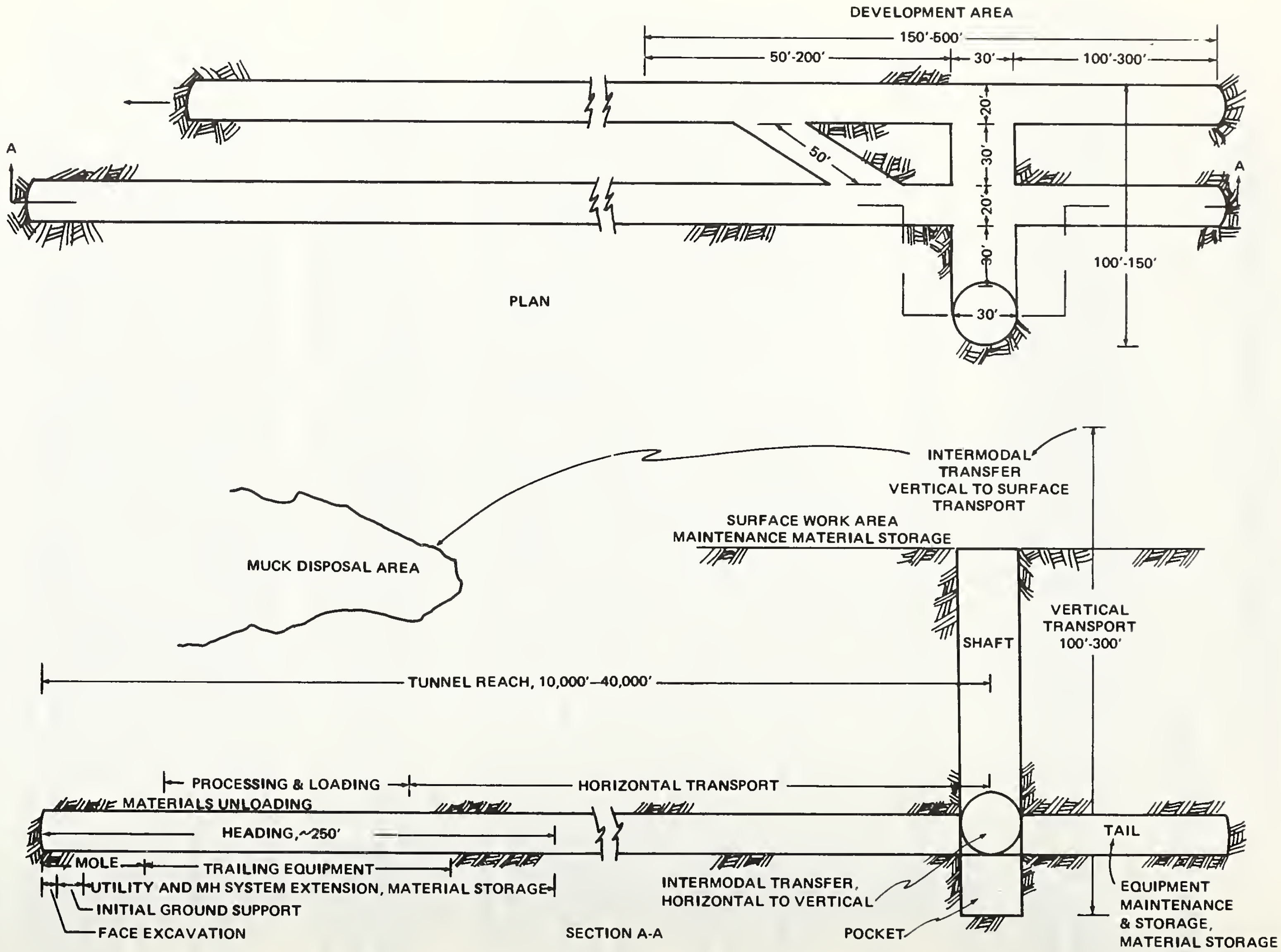

FIGURE 2. TYPICAL TUNNEL CONFIGURATION

possible to avoid the cost of shaft excavation solely for access to the tunnel. Shaft excavation is by drill-and-shoot or other appropriate method at a horizontal face advancing downward from the surface opening. A crane is used to lower and raise men and materials between the surface and shaft face during excavation. During construction of the tunnel, the only function of the shaft is vertical transport of men, materials, and equipment.

The surface work area at the shaft opening is usually smaller than the contractor would like to have due to lack of available space in urban locations. This results in inefficient surface operations. The principal operations in the surface work area are materials and equipment receipt, storage and handling, temporary storage of muck, loading muck onto heavy trucks for disposal, shop fabrications, repair of equipment, supervisory functions (safety, payroll, engineering, etc.), parking, power substations, compressed air plant, and ground water disposal facilities.

Muck is transported, usually by a contract haulage firm, over urban streets to a disposal area or to a storage area if the muck is suitable for future use as a construction material.

If access to the tunnel is through a portal rather than a shaft, no intermodal transfer of materials is required between the surface work area and the heading. Also, the functions of the development area are transferred to the surface work area at the portal. Thus, the portal access configuration is less complex and less expensive than the shaft access configuration and is used whenever possible.

Access

The more common tunnel access possibilities are illustrated in Figure 3. Portal access (type A) to urban mass transit system tunnels is usually found only in suburban areas at the ends of underground segments of the transit system. Unless the end of the underground segment corresponds with a decrease in the surface elevation, the portal access will be through an inclined tunnel segment (slope access, type B) to reach the depth of the running tunnel. These inclined tunnel segments for conventional rail systems are limited to about 4 percent grade by the grade climbing ability of the transit system.

As an alternative to the conventional rail transit system, a gravity assist concept has been investigated (18). This concept uses gravity, by profile grading of the guideways between stations, to help accelerate and decelerate trains in order to conserve electrical power and/or to decrease transit time. Guideway gradients up to ten percent, to achieve a drop of about 100 feet between stations, are suggested. If this concept were used with surface stations, all tunnel segments between stations would have slope access (type B) at each end. If the concept were used with subsurface stations, access to the horizontal tunnel segments would be through a combination of a shaft and a sloped tunnel segment (type C). If stations were spaced at less than 2,000-foot intervals, there would be no horizontal tunnel segments. With slope access of greater than four percent, the conventional rail haulage system used during tunnel construction would be modified to provide grade climbing ability.

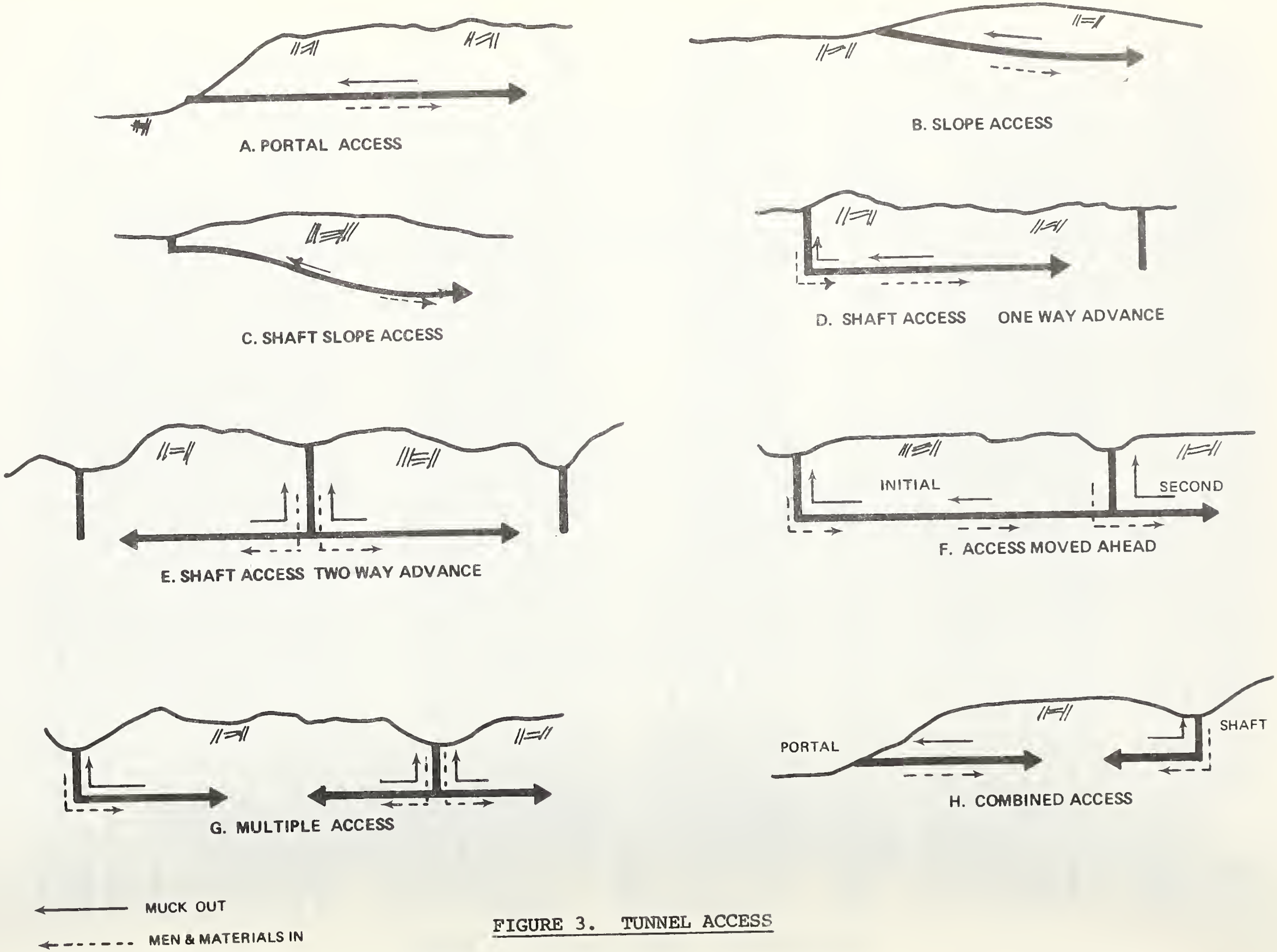

FIGURE 3. TUNNEL ACCESS

The tunnel access most frequently found in urban areas is single shaft access (type D). The lack of surface space available for the construction yard at some ventilation shafts may dictate that the tunnel be advanced in both directions (type E) from a shaft between the limits of the construction project. If both headings are driven simultaneously to gain the economy of reduced overhead and better utilization of work crews by alternating the crews between the headings, the material handling rate through the shaft will be doubled.

In long tunnels (greater than 10,000 feet) it may be desirable to move the access ahead (type F) to shorten the underground haul distance and to allow final lining to be completed in the excavated section. This approach could increase or decrease the environmental impact of surface haulage depending on the direction in which the tunnel is driven in relation to the location of the muck disposal area.

Multiple and combined access (types G and H) may be used when tunnels must be constructed rapidly. This produces a situation similar to two separate jobs and is seldom justified unless time is the prime consideration or the contractor obtains the jobs by separate awards. The material handling situations for access types G and H are identical to those of access types A through E.

Configurations

Figure 4 illustrates typical tunnel shapes and transit system configurations. Horseshoe tunnels are most common when drill-and-shoot excavation is used. Straight sidewall (wide or arch) tunnels are used with drill-and-shoot excavation in competent ground. Cut-and-cover excavation always produces vertical sidewall (usually rectangular) tunnels. Circular tunnel sections are generally the most economical to excavate and to support. They are produced by tunnel boring machines or shields.

Tunnels for a dual track transportation system are used in the transition zone at the ends of stations and when the tunnel is produced by cut-and-cover excavation. In the United States, almost all (except New York City) running tunnels produced by underground excavation between stations are for single track transportation in parallel tubes. Dual track circular tunnels or single track vertical sidewall (arch or wide) tunnels are seldom found in modern urban transit systems.

Construction Activities

The activities typical of an urban tunnel construction project are summarized in Figure 5. Activities are indicated by rectangular boxes. Alternative methods of performing some of the activities are indicated by oval boxes.

Excavation. Tunnel excavation is accomplished with either a cyclic or a continuous method, depending largely upon the type of material being excavated and the tunnel size, shape, orientation (slope and alignment), and length. Cyclic methods are the oldest and remain the most versatile and dependable. Continuous methods are not truly continuous since excavation

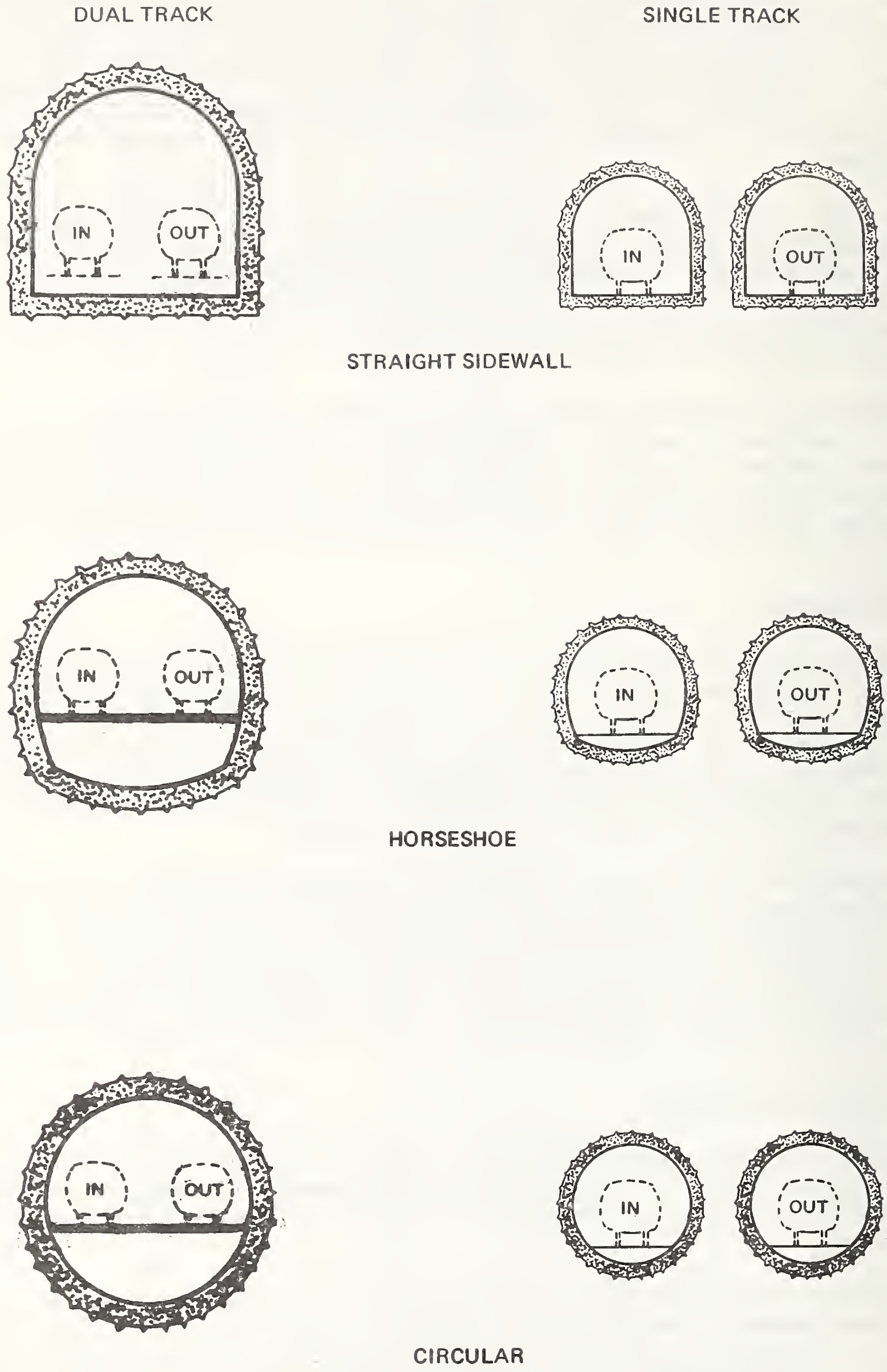

FIGURE 4. TUNNEL SECTIONS

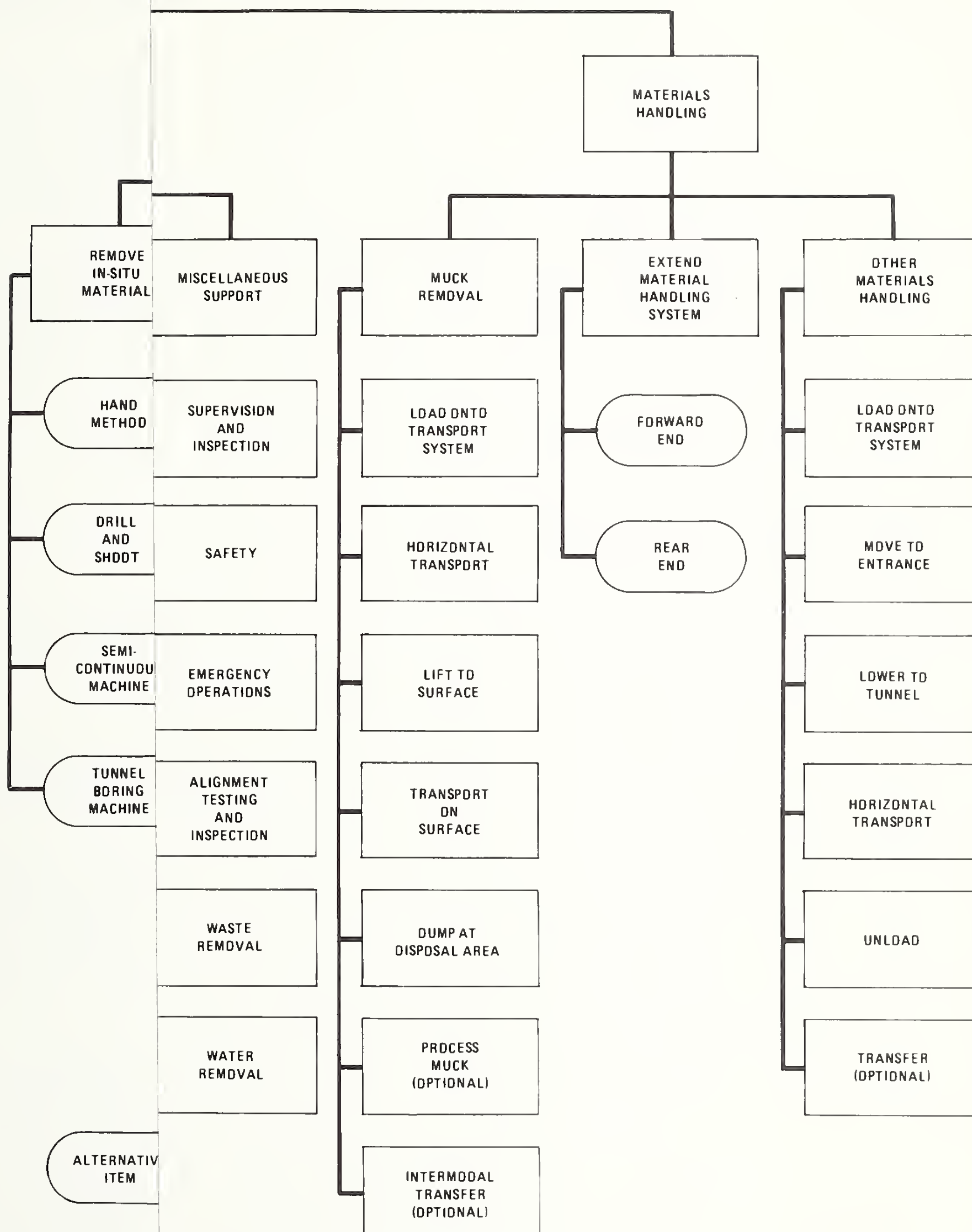

FIGURE 5

ACTIVITIES OF TUNNEL CONSTRUCTION

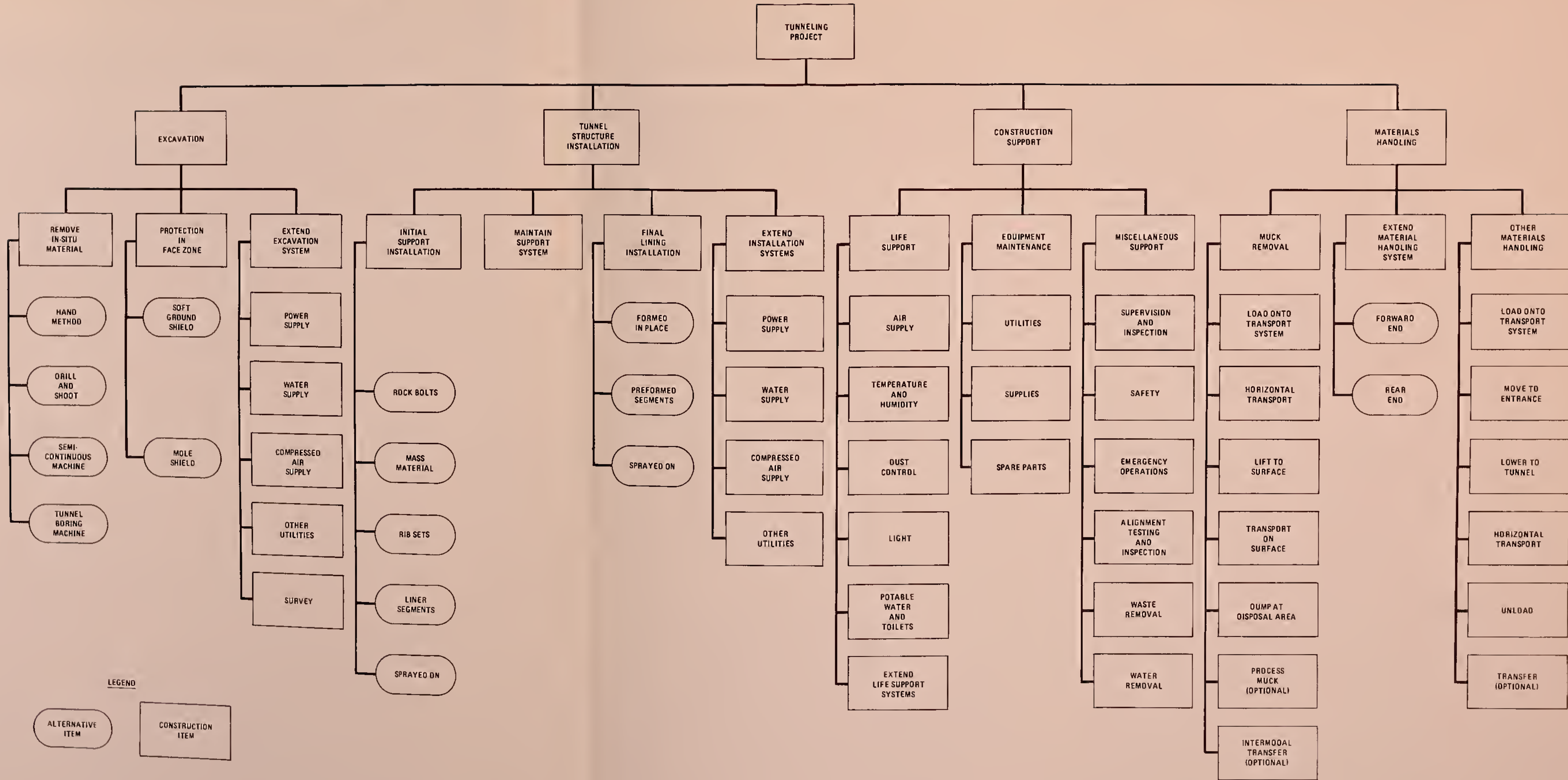

FIGURE 5

ACTIVITIES OF TUNNEL CONSTRUCTION

must be stopped to advance the excavation machine and to change cutters or digger parts. However, when continuous methods are used with extensive planning, good organization and supervision, and uniform ground conditions, remarkable rates of advance can be achieved.

Cyclic excavation methods use a hand-mine shield in soft ground and drill-and-shoot methods in rock. A hand-mine shield is an open-ended steel cylinder thrust ahead by hydraulic jacks reacting on previously erected liner rings. Miners excavate the ground in the upper compartment of the shield allowing the spoil to fall to the lower level. A mucking machine excavates the material from the lower compartment. Advance is usually in 30-inch increments. At the end of the advance, the jacks are retracted and a ring of liner segments is erected within the tail shield. The annulus left by removal of the shield is filled with pea gravel and grouted. Progress is normally from 15 to 30 feet per day. Muck varies from wet, runny material to large clods of clay.

Drill-and-shoot excavation is commonly used in the following situations:

a. When the rock is too hard to economically excavate with a mole

b. When the tunnel is too short to economically use a mole

c. When the rock is so treacherous or unpredictable that it precludes using a mole

d. When the tunnel section is other than circular

e. When the tunnel section is too large (greater than 40 feet) for excavation by a mole

In almost all other situations, mole excavation is more economical than drill-and-shoot, especially when a final lining must be installed, requiring that drill-and-shoot overbreak be filled with concrete. Furthermore, moling in competent rock produces a smooth excavated surface that may eliminate the need for a final lining.

Drill-and-shoot tunnel excavation employs heavy pneumatic or hydraulic drills positioned by hydraulic cylinders and booms mounted on a mobile platform or "jumbo," generally mounted on rubber tires for short tunnels and rail for long tunnels. One and one-half or two-inch diameter holes are drilled and charged with explosives. The depth of a round varies from 4 to 12 feet depending on ground conditions. The jumbo is moved away from the face, the explosives detonated, and the muck loading equipment moved in. Supports are usually erected after mucking when the jumbo is moved back into the heading. Typical progress is 20 to 60 feet per day, averaging 30 feet per day. Muck consists of sharp, angular fragments from sand size to boulders 4 feet and larger on a side. Running tunnels are excavated full-face, whereas stations, due to their size and often marginal rock conditions, are excavated with a multiple drift and bench method.

A continuous drill-and-shoot excavation method using special equipment is being developed (63, 64). It is projected that advance rates about four times (120 feet per day) those of current conventional drill-and-shoot methods will be achieved when the equipment and technique are fully developed. The muck produced from continuous drill-and-shoot excavation would have characteristics similar to those of muck from conventional drill-and-shoot.

Continuous excavation methods in soft ground employ either a backhoe-like digger arm or a rotating cutterhead (full face drumdigger) within a shield. The digger shield is widely used because it is capable of excavating ground containing boulders as well as fines. Another advantage is that it affords excellent access to the tunnel face for control of adverse ground conditions, whereas rotary cutterheads within a shield minimize access to the face and boulders cannot be excavated. Rotary cutterhead shields can be used in very weak and flowing soils that will flood digger shields. The "bentonite mole" is a rotary cutterhead shield with the addition of a sealed cutterhead chamber with a lock for muck removal and a seal between the tail shield and the outside of the erected liner ring. Segments are erected within the tail shield of these machines as with a hand-mine shield. Progress is cyclical in that excavation is stopped while the segment is built, but is continuous in that excavation is much more rapid than with hand-mine shields. Progress is from 30 to 50 feet per day for rotary cutterhead shields to 40 to 80 feet per day for digger shields. Rotary cutterhead muck varies from slurried fines to pieces and lumps of clay. Digger shield muck varies from wet, runny material to 3-foot boulders.

Continuous excavation in rock is performed with drum miners or tunnel boring machines. A drum miner is a rotating drum, fitted with carbide cutting tools, mounted on a hydraulically positioned boom on a crawler carrier. The drum is thrust into the tunnel face by the carrier and is swung around the face with the boom. The muck falls to the invert where a gathering arm loader feeds it to a drag flight conveyor. Rock support is erected alongside the miner behind the drum. The machines are used in non-circular, soft rock tunnels. Advance may be 10 to 40 feet per day. Muck is generally small fragments, chips and fist-size pieces with some larger boulders formed by rock jointing.

A tunnel boring machine (TBM or mole) consists of a full-face rotating cutterhead equipped with hardened-steel, rolling-disc cutters. The mole anchors itself in the tunnel by thrusting across the diameter of the tunnel to grip the tunnel sidewalls. This provides a base from which to thrust the cutterhead forward into the face. Buckets mounted on the periphery of the cutterhead scoop up and elevate the muck as the cutterhead rotates at 4 to 6 rpm, and then discharge near the apex of rotation onto a belt conveyor that transfers the muck into the material handling system. Rock support is installed as close to the cutterhead as the confines of the tunnel and the bulk of the mole will allow. Advance generally varies from 50 to 200 feet per day, averaging up to 125 feet per day. Mole availability is typically from 80 to 90 percent. Mole utilization is typically only 30 to 60 percent due to delays from ground conditions and maintenance. Mole use is normally limited to rock with compressive strengths of less than 20,000 psi with occasional lenses of 40,000 psi rock. Muck size depends on the hardness

and condition of the rock being excavated and the design of the cutter head. It varies from fine sand-size particles to 18-inch boulders with numerous elongated, flat, hand-size chips. Alignment and grade must be maintained by continuous surveys as the heading advances. In modern tunneling, this is usually accomplished by a laser beam providing a line-of-sight. This device is attached to the wall of the tunnel a few hundred feet behind the heading. The various excavation methods are summarized in Table 6.

Initial Ground Support. Most transit system tunnel excavations require initial ground support at the heading. Even tunnels in very high quality rock are usually supported by rock bolts for safety and psychological reasons. Support is placed as close to the face as possible for safety, to mobilize the self supporting capability of the rock, and to minimize earth subsidence at the ground surface. When cyclic excavation methods are used, installation of the initial ground support adds another step to the cycle, thus delaying the advance as well as requiring additional materials haulage and storage. With continuous excavation methods, initial ground support is installed simultaneously with the heading advance, thus further conjesting the already crowded work space at the heading and interfering with the excavation and muck removal activities.

Rock bolts, commonly 6 to 8 feet long, are used in the best rock conditions. These are usually 3/4-inch round steel rods secured with an expansion anchor, or 1-inch rebar anchored with epoxy resin. Bolts are normally placed on a 4x4-foot pattern in the upper one-third of the tunnel circumference so that 4 to 6 bolts would be placed every 4 feet of length in a 20-foot tunnel. Rock bolt accessories often used are 6x6-inch bearing plates, steel straps spanning between the bolts, and chain link fabric to catch minor rock falls.

Steel sets, consisting of wide-flange steel beams curved to the tunnel section are used to support less competent rock. These 6-inch or 8-inch sets are usually spaced on 4- to 6-foot centers and tied together with steel rods. Timber, usually 3x8 or 4x6 inches, is placed around the outside of the set and the entire unit is held in place against the rock with wooden wedges. In soft ground tunnels, initial support is often provided with Coeur d'Alene lagging consisting of 4x6-inch timbers placed tight together between the flanges of the beams and secured in place by wooden wedges.

Liner segments of cast iron, fabricated steel or precast concrete are used in circular soft ground tunnels that require compressed air for face support or in circular tunnels where it is advantageous to use the segments as the final lining as well as the initial lining. Segments are commonly from 30 inches to 5 feet wide, using 4 to 8 pieces to form the full circle. Liner plates of 3 to 10 gage steel pressed and rolled to form corrugations and flanges are used in conjunction with steel sets in hand-mine shields and in zones of bad ground in other tunnels. Concrete is usually added as a final liner inside liner plates. Pea gravel and/or grout may be used behind liner segments to fill voids.

TABLE 6. SUMMARY OF EXCAVATION METHODS

Method	Ground Condition	Advance Rate (ft/dy)	Muck Characteristics
Cyclic			
Hand-Mine Shield	Soft	15 - 30	Wet, runny material to large clods of clay.
Drill-and-Shoot	Rock	20 - 60	Sharp, angular fragments from sand-size to boulders 4' or more on a side.
Continuous			
Digger Arm/Shield	Soft	40 - 80	Wet, runny material to 3-foot boulders.
Cutter Head/Shield	Soft	30 - 50	Slurried fines to lumps of clay.
Drum Miner	Soft Rock	10 - 40	Small fragments, chips, and fist-size pieces with larger boulders from rock jointing.
Tunnel Boring Machine	Soft to Medium Rock	50 - 200	Sand size to 18-inch boulders with numerous elongated, flat, hand-size chips.
Drill-and-Shoot	Medium to Hard Rock	< 120	Same as cyclic drill-and-shoot.

Shotcrete, a mixture of sand, aggregate, cement, water, and accelerator applied pneumatically, 2 to 12 inches thick, is sometimes used on tunnel excavation surfaces for support. This material is usually used in drill-and-shoot excavations in conjunction with rock bolts or steel sets. Shotcrete is seldom used in moled tunnels because:

a. Proper application is difficult. The mole and auxiliary equipment so fill the tunnel that proper nozzle distance and angle are impossible.

b. The smooth moled surface minimizes adhering of the shotcrete to the rock, thus requiring a full circle application for support.

c. The mole grippers break the shotcrete and to apply it behind the grippers negates the advantages of immediate application.

d. Shotcrete rebound causes mole maintenance problems, and a difficult job of waste removal.

Grout is occasionally used to stabilize short stretches of soft ground tunnels or extremely bad ground in rock tunnels and is used to seal off water inflows.

Compressed air is used to stabilize the excavation face in soft ground tunnels excavated below the water table so excavation may proceed without material flowing uncontrolled into the heading. Cast iron or steel segments are normally used to support these tunnels.

Final Lining. Most transportation tunnels include a final lining of concrete, often reinforced with steel. This lining is generally formed in place after completion of excavation of the tunnel. Beginning at the most recently completed end of the tunnel and working back to the access shaft, concrete is usually placed in the invert first and then the arch, followed by any miscellaneous placements such as walkways or divider walls. Alternate methods of placing are arch first and then invert, or full circle. The concrete lining in transportation tunnels is usually placed intermittently, with the area for tomorrow's placement prepared after today's placing is complete. For urban tunnels, concrete is usually delivered to the project from a concrete supplier in transit mix trucks and transported to the forms by:

a. Railcar

b. Transit mix truck

c. Pipeline

d. Conveyor

e. Drop pipe to rail car or conveyor

The concrete then is placed into the forms by:

a. Hydraulic pump

b. Conveyor

c. Compressed air gun

Economics usually requires that the concreting system utilize the same type horizontal transport system as used during excavation.

Construction Support. Utility lines must be installed as the heading advances to supply the working area with ventilation, compressed air, drill water, electric power, lighting, communications, and guidance, and to remove inflow and waste water. Space must be provided at the heading for these utilities and for work crews to extend them. These extensions of utility lines are usually made in increments of 20 to 40 feet. More frequent additions to the supply lines must be made for continuous excavation methods than for cyclic methods due to the faster rates of heading advance.

Ventilation air is usually supplied by exhausting air through a 30- to 54-inch light gage steel fan line hung from the back or side (above the springline) of the tunnel. Other utility lines commonly vary in diameter from 2 to 8 inches. Fan line, water supply and waste water lines, and compressed air line must be extended at the same rate as the face advance rate. This requires transport of pipe, fittings, and support brackets from the surface work yard to the heading for installation.

The electric power and lighting system consisting of high-voltage transmission cable, connectors for high-voltage equipment, step-down transformers, low voltage wiring, incandescent bulbs or fluorescent tubes, and mounting insulators and brackets must be extended as the heading advances, and bulbs or tubes must be replaced periodically.

Potable water is provided in portable cans. Toilet facilities are self-contained chemical units which are moved ahead with the work zone.

Spare parts and supplies for the excavation and ground support installation equipment also must be transported to the heading and stored there for use as needed to minimize delays to the excavation equipment.

The construction support activities are performed intermittently and do not add significantly to the load imposed on the material handling system. The major impact of the construction support activities on the material handling system is the added requirement that it be able to stop and start at various locations in the tunnel to transport personnel, special equipment, and supplies without interfering with continuous operations at the heading.

Materials Handling. The two basic functions of the materials handling system are to remove muck from the heading and to transport men, equipment, and materials in either direction between the surface work yard and the heading. Both horizontal and vertical transport are included in most urban tunnel projects. Muck removal provides the greatest tonnage and volume flow

of material and is the primary consideration in the design of any tunnel haulage system. But transport of equipment and materials, which requires great flexibility in the system to handle the wide variety of shapes, sizes, and weights, must be given careful consideration. Characteristics of the materials to be transported are determined by the material excavated and by the excavation and initial ground support methods used. Processing of these materials (e.g., separating, packaging, mixing) is usually performed at the surface work area to minimize the underground space requirement. A minimum of transfers from one mode of transportation to another is desirable as each transfer adds to the material handling cost, to the complexity of the system, and to the possibility of increased downtime. Mechanisms for loading, unloading, and transfer of materials must be compatible with the material and the transport equipment. These transfer mechanisms are sometimes major cost elements in a material handling system.

Horizontal transport underground is primarily by trains traveling on two rails or by rubber tired vehicles. These require filling of the invert in circular tunnels. Conveyors are used to transfer muck from the head of mechanical excavators to the loading point for the transport system. Locomotives hauling trains of muck cars and supply cars are normally used for horizontal transport in:

a. Tunnels longer than 5,000 feet

b. Tunnels of circular section

c. Narrow tunnels that are difficult to widen for passing zones

d. Tunnels with grades less than 4 percent

Trucks with dump bodies are loaded with muck by front-end loaders, and flatbed trucks or special design rubber tired vehicles are used to transport men and materials for:

a. Hauls from 1,000 to 5,000 feet

b. Flat bottomed tunnels

c. Tunnels wide enough to pass two vehicles

d. Tunnels with grades less than 20 percent

Load-haul-dump units (LHD), diesel powered, low profile, self loading haulers, are used in:

a. Less than 1,000-foot hauls

b. Tunnels with grades up to 35 percent

c. Development work

Vertical transport is most commonly by cable hung skips, cages, or muck boxes lifted by cranes or hoists located at the top of the shaft. Bucket

elevators and inclined conveyors have been installed for lifting muck on recent jobs in Washington, D.C. and Chicago.

Surface haulage of muck to disposal areas is usually subcontracted to trucking firms using conventional 10-wheel trucks. These trucks add to the congestion of the surface traffic and have adverse environmental effects of dust, noise, and vibration.

These material transport systems when properly selected, designed, installed, and maintained are able to satisfy the material handling requirements of current tunnel excavation and ground support methods. As improvements are made in excavation and initial ground support methods, the material handling system capacity must be expanded to keep pace with the heading advance.

SPECIFIC PROJECTS FOR STUDY

To provide a basis for evaluation of the adequacy of present and developing materials handling equipment to meet the requirements for future urban mass transit tunnel construction, it is necessary to identify ranges for parameters which influence the material handling system and to define specific projects for study.

Tunnel Shape and Size

Saulnier (73) conducted a survey of dimensions for rapid transit tunnels existing and planned in the United States. Rectangular was found to be the most frequent shape. However, as this shape is produced only by cut-and-cover excavation methods, it is not considered in the evaluations for reasons indicated in Section 1. Straight sidewall and horseshoe sections (Figure 4) are produced by drill-and-shoot and drum-miner excavation. It is not anticipated that the material handling rates required for these excavation methods will exceed the current capabilities of the conventional material handling systems in the foreseeable future, even if the continuous drill-and-shoot technique is fully developed. Furthermore, findings from a study of materials handling in circular tunnels are applicable to vertical sidewall and horseshoe tunnels if consideration is given to the more usable floor space available, the slightly greater muck quantity per tunnel foot, and the larger lump size of the muck produced by drill-and-shoot excavation. Therefore, the tunnel shape selected for evaluation of material handling systems is circular.

Saulnier (73) indicates no dual track circular tunnels existing or planned for U.S. transit systems. The single track tunnels vary in finished (final liner installed) diameter from 14'0" to 20'5" with the majority between 15'3" and 18'9". A finished diameter of 17'6" was selected as representative of the upper range of the circular tunnels surveyed. This produces a muck rate greater than would occur for the average transit tunnel. As the tunnel diameter increases, the muck rate increases with the square of the diameter; but the space available for larger muck haulage equipment also increases, tending to relieve the stress on the material handling system.

Circular tunnels in London (16) and in Canada (60) are generally smaller, ranging from 10 to 15 feet, than those in the United States. Although it

appears unlikely that the United States will build many transit tunnels in this range in the foreseeable future due to the car sizes available from the established rail car manufacturers and the accepted section blockage ratio, a lower bound of 12'6" for tunnel diameter was selected. An upper bound of 29'0" was selected to be representative of the maximum width of double track horseshoe and wide tunnels, even though very few of these tunnel shapes are included in present transit plans.

Finished tunnel diameters of 12.5, 17.5, and 29 feet require excavated diameters of 15, 20, and 32 feet respectively.

Advance Rate

The average daily advance rate of the heading is determined by the rate of excavation of the face and the frequency and duration of interferences which prevent excavation from taking place. While excavation is in progress, the rate of excavation (measured as inches penetration per minute in the case of mole excavation) varies due to the variation in ground conditions and the condition of the cutters.

The occurrence of interferences which prevent or delay the excavation activity also is highly variable. Thus, the daily advance rate expressed as feet per day (fpd) can vary from zero to a maximum daily advance which occurs only once during the job. Job experience for mole excavation indicates that the net result is an average advance, in feet per day for the duration of the excavation period, which is about one-half the equivalent of the average penetration rate, and a maximum advance rate which is about twice the average daily rate. Table 7 illustrates the advance rates presently achieved and projected for the future. This table was developed from discussions with tunneling contractors and was confirmed by a leading manufacturer of moles (71). Any significant improvement in the rate of advance for soft ground tunneling is dependent on improvements in the emplacement of initial ground support. Even then, hand-mine shield tunneling would be limited by the slow rate of hand excavation. Significant improvement in drill-and-shoot excavation is dependent on development of a continuous drill-and-shoot method. Improvement in mole advance rate depends upon improvements in initial ground support emplacement, in the cutters and cutter bearings, and possibly in other mechanical parts of the mole. Development of innovations such as water jet assist may contribute to improved mole penetration rates.

Tunnel Length

As the heading advance rate increases, it is necessary to increase the length of tunnel assigned to a project in order to maintain a reasonable balance between the length of time required for tunnel excavation and that required for mobilization, development excavation, erection and moving the mole, and demobilization. Currently for a 10,000-foot tunnel project, the excavation time is about 30 to 40 percent of the project time (about seven months moling out of an 18-month project). If the penetration rate increased to 10 feet per hour (fph), equivalent to 2 inches per minute (ipm), rather than 6 fph (1.2 ipm) for the same size job, the excavation time would be reduced to about 25 percent of the project time (about 4 months out of 16 months). For a penetration rate of 25 fph, moling time would be only a

TABLE 7. HEADING ADVANCE RATES

Penetration rates are in inches per minute
Advance rates are in feet per day

Excavation: Type / Method	Current				Projected							
					Near Term (1980+)				Far Term (1990+)			
	Penetration Rate		Advance Rate		Penetration Rate		Advance Rate		Penetration Rate		Advance Rate	
	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.	Avg.	Max.
Soft Ground Hand Mine Shield	---	---	15	30	---	---	15	30	---	---	25	* 50
Soft Ground Digger Shield	---	---	40	80	1	1.5	50	100	1.5	2	100	* 150
Hard Rock Drill-and-Shoot	---	---	30	60	---	---	35	70	2	3	130	** 250
Hard Rock Mole	1.2	2.0	75	150	2	3	120	240	5	7	300	*** 600

*Assumes methods developed for more rapid ground support placement.
**Assumes continuous drill-and-shoot method developed.
***Assumes development of improved cutters and other developments.

little more than 12 percent of project time (about 1.6 months out of 13 months). Therefore, for the improved penetration rates projected, tunnel lengths per project were assumed to be 20,000 feet for a penetration rate of 10 fph and 80,000 for 24 fph. This causes the excavation time of the project to be between 35 and 45 percent in all cases.

Tunnel Grade and Curvature

Currently, transit tunnel grades do not exceed 4 percent as this represents the maximum assured grade climbing ability of a rapid transit train. However, gravity assist rapid transit systems with grades up to 10 percent have been investigated (18). Therefore, to identify material handling problems which might occur during construction with selection of this concept, dipping and rising grades of 10 percent have been assumed for special variations of rapid transit tunnels after 1990.

Curve radii in older transit systems are often quite short as the routes attempted to follow street rights-of-way. It is anticipated that in the pursuit of higher average speeds and with the possibility of more favorable right-of-way statutes, curve radii will become greater in the future. Therefore, it is assumed that sometime after 1990, minimum curve radii of less than 1,000 feet will seldom be designed into a transit system.

Shafts

Analysis of data presented in a recent survey of geologic information pertinent to tunneling in selected urban areas (13) indicates a distribution of soil thicknesses in potential transit system areas approximately as follows:

TABLE 8. DISTRIBUTION OF SOIL THICKNESS

Soil Thickness, Feet	Percent Occurrence
20	28
20-50	44
50-150	8
150	20

It is always desirable to locate a tunnel either entirely in soil or entirely in rock to avoid the high cost of mixed-face excavation. It also is desirable to have a minimum depth of 30 feet to the back of the tunnel in underground excavation to minimize interference with utilites and structural foundations and to minimize surface subsidence. If the tunnel is in rock, it is desirable to have 20 to 30 feet of rock cover over the tunnel to take full advantage of the self supporting characteristic of the rock. Thus, for a 20-foot diameter tunnel, the minimum depth from surface to tunnel invert or from the soil-rock interface to the invert is 50 feet. However, about 40 percent of the time, tunnels placed at this depth would have mixed-

face conditions (Table 8). About 30 percent of the time the tunnel would be in rock but most of this time there would be inadequate rock cover. Therefore, it can be assumed that about 70 percent of the time the tunnel invert would be at a depth greater than 50 feet to assure a rock tunnel with adequate rock cover. An invert depth of 100 feet would assure these desired conditions for the entire 70 percent.

For about 30 percent of the time, invert depths of 50 feet would provide soft-ground tunneling conditions. However, if the invert depth is at 200 feet, the tunnel would be in rock with adequate rock cover about 80 percent of the time. If improvements in rock tunneling compared to soft ground tunneling continue, it can be assumed that deeper locations to reach rock strata may be desirable after 1990. In fact, some urban tunnels in the United States and other countries are currently in the 150 to 220-foot range. Therefore, an invert depth of 200 feet is assumed for the 1990+ time period to identify the impact of increased lifting height.

Initial Ground Support

To achieve the advance rates indicated, very little delay time due to installation of initial ground support can be tolerated. Therefore, it is assumed that only 20 percent of the tunnel requires more than rock bolt support. This support is assumed to be steel sets over 270 degrees of the tunnel circumference with the sets placed on 5-foot center-to-center spacing. Twenty percent of the tunnel length is assumed to require epoxy bolts in rows of 8 bolts each spaced 4 feet between rows. The remaining tunnel has expansion bolts in 4-foot rows of 6 bolts each.

TUNNEL PROJECT PARAMETERS

The approach selected for comparative evaluation of alternative material handling systems is to define "base case" projects for the 1980+ period (near term) and for the 1990+ period (far term) using conventional rail and hoist material handling systems. Alternative material handling systems are then substituted for the conventional systems in the near term and far term periods. Total project cost estimates, including a complete material handling system capable of transporting all incoming and outgoing materials, are then made for each alternative material handling system and the base case system in each time period. In this way, all impacts on the project cost due to the various material handling systems can be identified. The parameters of the near term (1980+) and far term (1990+) cases are summarized in Table 9. Major emphasis is placed on the "base" parameter values.

TABLE 9. TUNNEL PROJECT PARAMETERS

Parameter	Near Term (1980+)			Far Term (1990+)		
	Min.	Base	Max.	Min.	Base	Max.
Type of Ground	Rock					
Excavation Method	Tunnel Boring Machine					
Tunnel Section	Circular					
Tunnel Diameter						
Finished (ft)	12.5	17.5	29	12.5	17.5	29
Excavated (ft)	15	20	32	15	20	32
Penetration Rate (inches/minute)		2	3		5	7
Advance Rate (feet/day)		120	240		300	600
Tunnel Length						
Per Job (feet)		20,000			80,000	
Per Reach (feet)	5,000	10,000		10,000	40,000	
Tunnel Grade (percent)	-4	0	+4	-10	0	+10
Curve Radius (feet)	250	750		750	1,000	
Shafts						
Section (feet)		30			45	
Depth to Invert (feet)	60	100		60	200	
Spacing (feet)		3,000*			3,000*	
Initial Ground Support						
270° Sets @ 5' c-c	4000TF = 800			16000TF = 3,200		
Epoxy Bolts @ 4' c-c	4000TF, 8/row = 8,000			16000TF, 8/row = 32,000		
Expansion Bolts @ 4' c-c	12000TF, 6/row = 18,000			48000TF, 6/row = 72,000		

*Same as Jet Propulsion Laboratory Study (18).

3. FLOW AND CHARACTERISTICS OF MATERIALS TRANSPORTED

Within an underground construction complex, the movement of men, equipment, materials, and muck is a two-directional flow of diverse substances. The outbound flow is dominated by muck removal and is influenced by other materials. Inbound flow is dominated by inbound muck removal equipment and the ground support and systems extension materials. Thus, inbound flow is influenced by a wider range of materials than the outbound flow. Consideration of the combined inflow and outflow determines the material handling system requirements.

FLOW CHARACTERISTICS

The flow of materials must follow the path established by the underground excavation. Usually, in an urban area, this consists of a relatively horizontal tunnel and a vertical shaft, although the vertical access may be an incline.

The speed of flow of materials is dependent upon the amount of material to be handled, the size of material transport container, and whether the material transport system is continuous or intermittent. Each type of material handling equipment has certain optimum speed characteristics. Higher speeds are generally more hazardous. Due to the closeness of the tunnel walls, man's sensation of speed in a tunnel is amplified greatly from that on the surface (traveling on a locomotive at 20 mph in a tunnel seems like 50 mph on the surface).

The quantity of materials involved may require that both inbound and outbound flow must occur simultaneously, thus reducing the sectional area available to flow in either direction. The various construction activities taking place further reduce the area for the material transport systems and impose extra safety requirements on the material handling equipment. This is especially critical at the heading.

Material transport systems must operate in a closed loop, that is, the transport equipment must return to its origin for reuse. When several types of equipment compose a material handling system, each type operates in a separate closed loop. Each type can operate at a different velocity, but they should have matched capacities for economical operation.

Transfers of material generally occur at the:

a. Heading; from the loading equipment to the hauling equipment.

b. Shaft; from the horizontal to the vertical material handling equipment.

c. Surface; from the vertical material handling equipment to the equipment for haul to the disposal site.

Since the transfer points are especially subject to problems (plugging, breakdown, environmental dust), the number of transfers should be minimized. Major transfers require either direct or remote, continuous monitoring to detect problems before they become serious.

Table 10 summarizes the types of materials handled in various locations during excavation and the direction of material flow.

A further requirement of the material transport system is that it have an adjustable flow capability which can be synchronized with the rate of penetration at the face. Haulage requirements are continuously changing due to changes in the penetration rate during moling* and variations in delay or shutdown of the mole due to equipment failure in any of the systems. In situations where installation of initial ground support, material transport or extension of the material transport system paces the heading advance, there also will be delays manifested by periodic shutdown of the mole or by mole operation at less than its full capability.

A typical muck rate pattern resulting from the effect of these variables is shown in Figure 6, which also shows a typical tunnel job schedule.

The two periods of tunnel excavation, for two parallel tunnels, total about eight months or about 30 percent of the job duration of 27 months. During a period of excavation, the daily advance rate (Figure 6B) varies from zero during times that the mole is not operating to a maximum or peak value for the job. The duration of mole shutdown varies from several days when major equipment failures occur causing zero advance for the day to as little as two minutes for advancing the mole grippers. Shutdowns of less than 24 hours duration occur every day. Some causes of shutdown, such as regripping and changing cutters are unavoidable and can be predicted with fair accuracy. Others, caused by equipment failure, often occur suddenly and at unexpected times. These short-term shutdowns allow some advance for the day, but hold the average daily advance for days in which the mole operates to a value significantly less than the peak value. The average daily advance over the entire excavation period is usually about 50 percent of the maximum daily advance for the job.

For a typical conventional job, requiring installation of steel sets over 20 percent of the excavation, the delays expressed as percent of the tunnel excavation period might be as indicated in Table 11.

The muck production rate is determined by the mole penetration rate rather than the daily advance rate. The major factors affecting the penetration rate while the cutter head is rotating are:

a. The hardness and other conditions of the rock

b. The condition of the cutters and the cutter bearings

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*Excavation by tunnel boring machine is used for discussion. The observations are similar for soft ground excavation and drill-and-shoot.

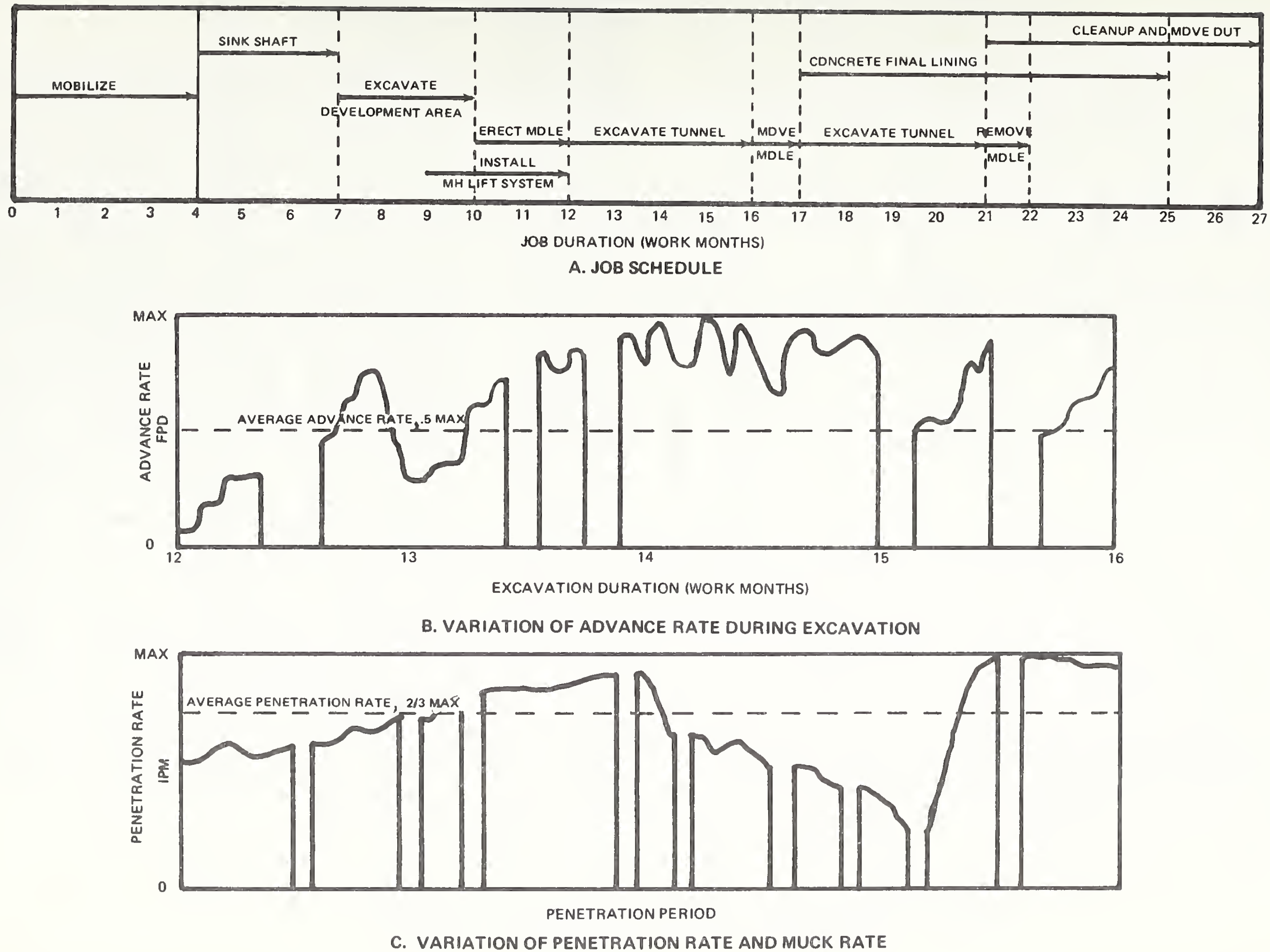

FIGURE 6. VARIATION OF MUCK RATE

TABLE 10. MATERIALS HANDLED & DIRECTION OF FLOW

Zone	Men	Equipment	Supplies: Parts & Lubricants	Supplies: Expendable Supplies	Utilities	Initial Support Materials	MH System Extension Materials	Muck	Final Lining Concrete
Face	↔			←				→	
Initial Ground Support	↔	↔	↔	←		←		→	
Utility & MH System Extension	↔	↔	↔	←	←	←	←	→	←
Tunnel	↔	↔	↔	←	←	←	←	→	←
Transfer	←↑	←↑	←↑	⤶	⤶	⤶	⤶	⤴	⤶
Shaft	↕	↕	↕	↓	↓	↓	↓	↑	↓
Portal Area	↔	↔	↔	←	←	←	←	→	←
Surface Transport	↔	↔	←	←	←	←	←	→	←

In, ← toward heading; Out, → away from heading; Up, ↑ ; Down, ↓ .

TABLE 11. SOURCES OF EXCAVATION DELAYS

Item	Percent of Excavation Time
Reset grippers	2.5
Install steel sets	10.0
Material handling system	3.0
Ventilation system	1.0
Electrical power system	1.5
Replace cutters	2.5
Repair mole	10.0
Repair material handling equipment	2.5
Repair rock bolt drills	1.5
Repair other equipment	0.5
Shift change	4.0
Startups and curves	11.0
Total Delays	50.0

c. The force with which the cutter head is shoved against the face

d. The rotation speed of the cutter head

Thus, while the cutter head is rotating, the penetration rate varies depending on the combined effect of these variables. Normally this variation is less than threefold, but it can be as great as tenfold. The penetration rate in inches per minute (IPM) averaged over all periods of mole rotation is usually found to be about one-half to two-thirds of the maximum penetration rate for relatively uniform rock.

In addition, there are brief, periodic shutdowns of the mole at the end of each stroke of 2 to 6 feet to reset the grippers. These shutdowns are from one to three minutes duration and occur at intervals of about 25 to 60 minutes. Also, replacement of cutters usually occurs daily during the latter part of the work week. This operation requires from one-half to two hours with the longer periods occurring toward the end of the week.

As the rate of muck production is related to the penetration rate and affected by downtime, it will vary on a minute-by-minute, hour-by-hour or day-by-day basis. The flow rate of incoming materials for initial ground

support and extension of the materials handling system must follow or keep ahead of this variation, at least on an hour-to-hour basis, if these activities are not to cause further delay of the excavation.

The haulage requirement is also continually changing because the length of the horizontal transport continually increases as the heading advances. For truck or rail haulage this requires ever greater speed between the heading and the shaft or the addition of more haulage units and the resulting increased need for vehicle passing in the tunnel.

SYSTEM DESIGN

Temporary storage is normally provided at interfaces between subsystems of a material transport system to smooth the peaks of material flow. This makes it possible to design the transport system for the average flow rate rather than the peak rate, thus improving the utilization of the system capacity. This intermediate storage is especially needed at the interfaces (mole/train, train/hoist, hoist/final disposal) of intermittent haulage systems.

Continuous flow systems, such as conveyors, can accommodate surges up to the design capacity of the system by increasing the transit velocity or by loading the equipment more heavily. Application is independent of the length of extension of the system up to the point where additional power must be added to maintain the required velocity. To accommodate surges beyond the design capacity of the system, temporary storage must be provided between the mole and the continuous material transport system.

Since rock muck has a swell factor of 1.7 to 2, (that is, it occupies 1.7 to 2 times the volume occupied before excavation) the space required at the heading for storage of muck, to allow for design of a material transport system with capacity matching the average penetration rate rather than the peak rate, would interfere with other operations in the heading. For example, in a 20-foot diameter tunnel with a penetration rate of two inches per minute average (three inches per minute maximum) the muck rate would be 200 loose cubic yards per hour average (300 loose cubic yards per hour maximum). For a transport system with a capacity of 200 cy/h to accommodate a penetration rate of three inches per minute for one hour would require a surge storage capacity of approximately 100 cubic yards. If this storage capacity became filled, the material handling system would delay the moling operation.

Normally, muck haul systems are designed to not delay the heading advance at the peak anticipated production of the muck loading equipment for some arbitrarily chosen haul distance (two-thirds or three-fourths of the length of the tunnel). The contractor may consider it not economical to provide full haul capacity at maximum tunnel length for maximum muck production. Some contractors may prefer to design the muck haulage system with a capacity less than that required for the peak muck production to increase the utilization of the system capacity, particularly if they anticipate the peak occurring infrequently and/or for short duration. An alternative to delaying the mole in these cases would be to provide surge storage between the mole and the transport system.

Another design concept which could be adopted if the material transport system consists of a continuous flow system combined with an intermittent flow system is illustrated in Figure 7. In this approach, the continuous system is designed to carry something less than the average muck flow to assure a high utilization of the continuous system capacity during periods of penetration. The muck produced which exceeds the capacity of the continuous system is transported by the intermittent system which is required to transport men and construction materials.

Concerns of tunneling contractors are that if the material handling system design is "fine tuned" to improve its utilization, the system will have less resilience to accommodate unanticipated material flow conditions. Also breakdowns of continuous systems put the entire system out of operation.

SYSTEM UTILIZATION

If the material handling system is designed to accommodate the muck rate resulting from the maximum penetration rate when the system is fully extended, the utilization of the system capacity (in ton-miles) during the excavation period is very low. This low utilization results from the facts that:

a. The average penetration rate (and muck production rate) is only one-half to two-thirds of the maximum rate.

b. The delay time (no penetration) is about 50 percent of the excavation period.

c. The horizontal transport system equipment is, on the average, only 50 percent installed and used as the heading advances through the tunnel reach.

As the vertical transport equipment is fully installed throughout the excavation period, it can be assumed for illustration that the total transport system is 60 percent installed on the average. This results in a utilization factor for the transportation system of (.67)(.50)(.60)(100) = 20 percent.

This leads to the observation that a transport system investment with only 20 percent utilization results in a high cost per ton-mile when compared to the same system installed in a mining operation or for overland transport where the utilization of purchased capacity may be 80 to 90 percent or more.

MATERIAL HANDLING OPERATIONS

The removal of muck from the heading to the disposal site requires a series of operations which vary depending on the muck characteristics and

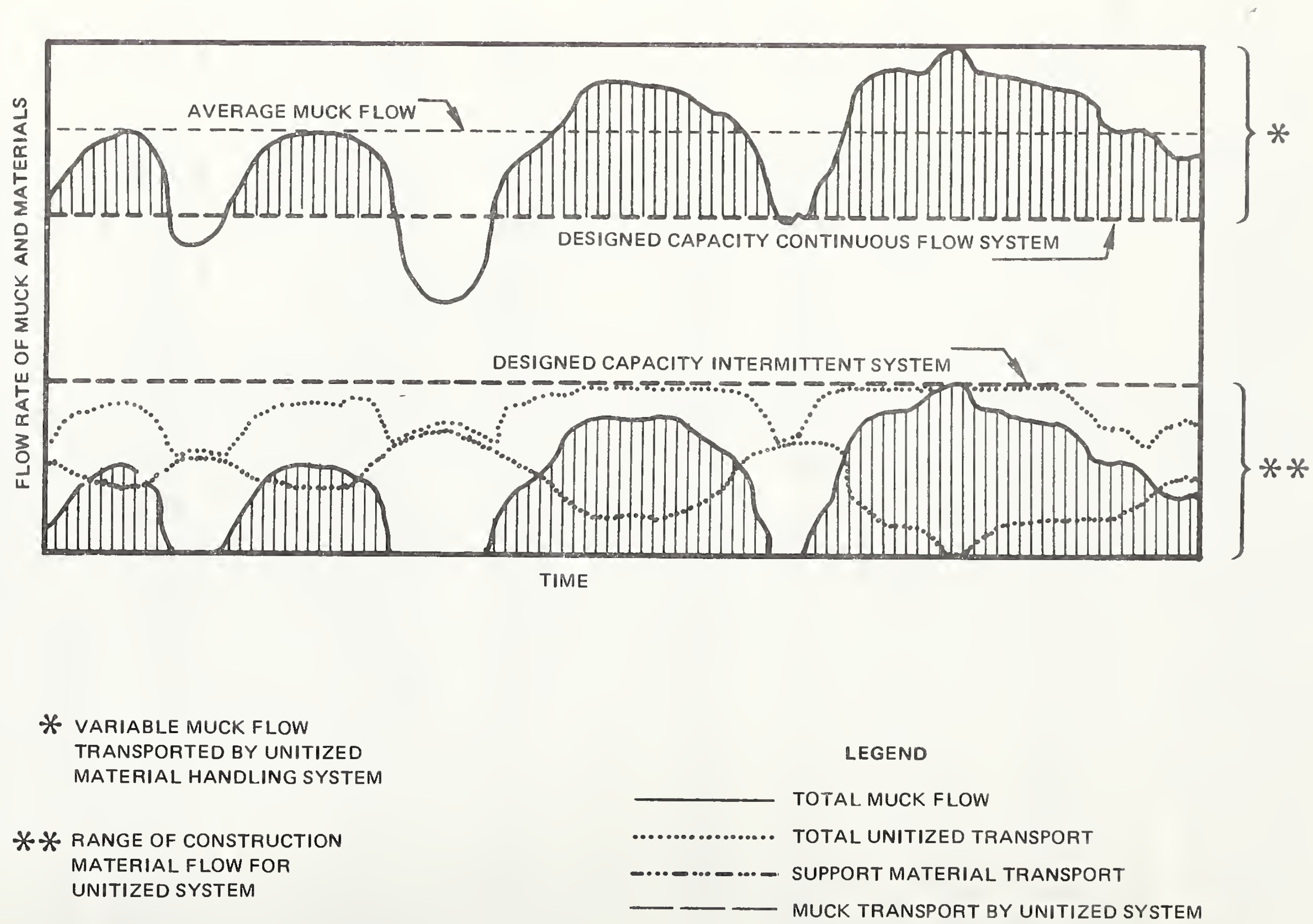

FIGURE 7. COMBINED CONTINUOUS AND INTERMITTENT TRANSPORT SYSTEM

the configuration of the material transport system selected. Typical operations for muck removal are:

a. Transport from excavator to horizontal transport system or processor

b. Process (if required)

c. Load into horizontal transport system

d. Transport through tunnel

e. Transfer (if required) to vertical transport system or processor

f. Process (if required)

g. Lift through the shaft

h. Remove from the transport system at the surface work area

i. Load into the disposal transport system

j. Transport through the urban area

k. Remove from the disposal transport system

The transport of materials and equipment to the heading also consists of several operations, as follows:

a. Load onto delivery vehicle

b. Transport through the urban area

c. Unload at the surface work area

d. Hold in storage awaiting need in tunnel

e. Load onto vertical transport system

f. Lower through shaft

g. Load onto horizontal transport system

h. Transport through tunnel

i. Unload at heading

j. Hold in storage until needed

k. Move into position for installation or use

MATERIALS TRANSPORTED

Materials that must be transported to support the tunnel construction process are indicated in Table 12.

TABLE 12. MATERIALS TO SUPPORT TUNNEL CONSTRUCTION

Material	Flow	
	Outbound	Inbound
Muck	X	
Men	X	X
Equipment	X	X
Supplies		X
Utilities		X
Initial Support Materials		X
MH System Extension Materials		X
Final Lining Concrete		X
Waste Materials and Scrap	X	

Muck is, by far, the largest quantity of material in terms of both mass flow (tons per hour) and volume flow (cubic yards per hour). Typical characteristics of muck produced by soft ground excavation and excavation in rock with drill-and-shoot and by moling are given in Table 13. Most of these characteristics are highly variable for each type of excavation. For example, the size, shape, stickiness and moisture content are dependent on

TABLE 13. MUCK CHARACTERISTICS

Item	Soft Ground	Rock	
		Drill-and-Shoot	Mole
Size Range, feet	-2	- 4	- 1.5
Muck Designation Number (20)	2	1, 2	3, 4
Shape	rounded	angular & sharp	angular, flat & sharp
Hardness, Moh	1-7	5-7	5-7
Abrasiveness	low	high	high
Specific Gravity, in situ	1.8-2.65	2.65	2.65
Swell Factor	1.5	1.6	1.7-2
Moisture Content, percent	<50	<5	<10
Angle of Repose, degrees	20	40	30
Stickiness	high	nil to low	low to medium
Density, t/cy (in situ)	1.5-2.2	2.2	2.2
Density, t/lcy*	1-1.5	1.4	1.3

*Based on lower value for swell factor.

the soil or rock characteristics which change throughout the length of most tunnels. The particle size of moled muck also is affected by the design of the cutters and the cutter head. This variability of characteristics requires that the material handling system must be capable of accommodating a wide variety of feed material conditions or processing must be provided to bring the muck characteristics within the range acceptable to the material handling system. The variation in moisture content and stickiness of the muck creates the most difficult material handling problems.

Table 14 presents the muck rates expressed as tons per hour (tph) and as loose cubic yards per hour (lcy/h) obtained for various types of excavation with the penetration rates indicated. The muck rates projected to the far term period for soft ground excavation and for drill-and-shoot excavation are in the range of those for the near term period when excavation is by tunnel boring machine in rock. Therefore, consideration of only rock excavation by mole in the analysis of material handling system alternatives will cover the range of material flow rates projected for other modes of excavation.

TABLE 14. MUCK QUANTITIES

Type of Excavation	Excavation Diameter (feet)	Advance Rate			Muck Rate	
		ipm	hpd	fpd	Weight tph	Volume lcy/h (4)
Soft Ground	20	2 (1)	15	150	175-260	175
Rock						
Drill & Shoot	23		13	130	340	250
Mole	20	2 (3)	12	120	260	200
Mole	20	3 (3)	16	240	400	300
Mole	20	5 (2)	12	300	650	500
Mole	20	7 (1)	17	600	900	700

ipm = Penetration rate, inches per minute.
hpd = Hours of penetration per day.
fpd = Heading advance rate, feet per day.
tph = Tons of muck produced per hour during penetration.
lcy/h = Loose cubic yards of muck produced per hour during penetration.

(1) Maximum penetration rate in the far term.
(2) Average penetation rate in the far term.
(3) Near term: 2 ipm = average; 3 ipm = maximum.
(4) Based on lower value for swell factor.

Typical examples of materials other than muck are listed in Table 15 with the order-of-magnitude dimensions of the space envelope occupied and the approximate weight per unit. The flow quantities of these materials (other than equipment) are shown in Table 16. The movement of much of the equipment is sporadic as it is moved to the heading on an as-needed basis and back to the shaft for repairs or when no longer needed at the heading. Some materials (material handling system extension) are moved to the heading on a regular but intermittent basis. For others, (ground support) the movement is sporadic depending on the ground conditions.

Rock bolts, being relatively short, straight steel rods or rebar banded into bundles for transport, present no material transport problems. Steel sets are usually fabricated so that four pieces make up a circle. For a 20-foot tunnel, each piece occupies a space about 4 feet by 15 feet by 1 foot and may weigh from 200 to 600 pounds. Except for their awkwardness due to their bowed shape, they present no material transport problem. Lagging and accessories are easily transported with the sets. All sets, especially those used in stations where each piece may weigh five tons, are difficult to handle at the erection stage. Concrete or steel segments, up to 5 feet wide by 15 feet long, are heavy (up to 3 tons) and awkward to handle. The major restriction placed on them by the requirements for transport is width to allow handling all the way to the heading where they are installed. Gravel for backfilling segments, shotcrete aggregate and cement, grout, and concrete for final lining are transported in bulk in special rail cars or trucks and offer no problems except for the additional congestion caused at the heading or if it is necessary to pass trucks in the tunnel. All equipment transported into the heading must be limited in size so that it will pass equipment emplaced in the heading.

Men are normally transported in a tunnel in specially fitted trucks or rail cars or in muck cars. Movement of men past the muck loading area to the heading is often restricted and sometimes hazardous. Heavy, bulky spare parts and lubricants often present transport problems in the heading area. System extension supplies are often long (rail, conveyor frame, and pipes) and difficult to carry past the muck loading equipment to the heading and are therefore installed behind the heading whenever possible. Power cable, being bulky and heavy, is transported on its reel on a special car, in a special cable box, or on a flat car.

The materials characteristics which are important depend on the type of material handling equipment to be used. Lump size is important for pipelines, bucket elevators and conveyors but not for rail or truck haul. Wetness and stickiness are important for all transport methods with the possible exception of hydraulic pipeline. Abrasiveness is of particular importance for pneumatic pipeline transport. The wide variation in size, shape and weight of the inbound materials precludes their transport by any means other than rail or truck. A primary requirement for a tunneling material transport system is that it must be capable of responding or conforming to changing or new situations to accommodate the wide variety of material sizes, shapes, weights and flow rates.

TABLE 15. TYPICAL MATERIALS HANDLED

Item	Approximate Unit Dimensions	Approximate Unit Weight, lbs
Equipment		
Transformers	2'x4'x4'	3,000-6,000
Ventilation fans	2' to 4'Øx4'	1,000-3,000
Compressors	4'x4'x4' to 6'x6'x6'	3,000-8,000
Welders	1'x2'x3'	500-1,500
Rock drills	1'x1'x4'	200-500
Grout mixers	3'x3'x3'	300
Grout pumps	2'x2'x5'	500-1,500
Crushers	5'x7'x9'	30,000
Water pumps	1' to 2'Øx2' to 4'	30-1,200
Muck cars	3'x4'x8' to 6'x8'x20'	6,000-16,000
Supplies		
Spare parts	.1'x.1'x.1' to 2'x10'x10'	.1-6,000
Electrical supplies	Various	10-1,000
Lubricants	3'Øx4'	400
Drill bits and steel	1"Øx 4' to 13'	10-60
Explosives	1'x1.5'x2'	60
Mole cutters	1.5'Øx1.5'	200-400
Oxygen and acetylene bottles	.7'Øx4'	
Small tools	.5'x.5'x.5' to 1'x1'x6'	10-100
Utilities		
Ventilation pipe and couplings	3' to 4'Øx20' to 30'	350-700
Compressed air pipe	.3' to .5'Øx20' to 40'	80-300
Clear water pipe	.2' to .3'Øx20' to 40'	70-160
Discharge water pipe	.3' to .7'Øx20'to 40'	80-450
Power cable 1,000'	6'Øx4'	2,000-3,000
Light line 100'	1'x2'x4'	60
Telephone line	2'Øx2'	50
Blasting line	.4'x1'x1'	20
Hangers/supports for the above	.5'x.5'x3'	20
Initial Support Materials		
Set segments and accessories	15'x4'x1'	200-600
Timber lagging	.3'x.5'x5'	40
Rock bolts bundle	.7" to 1"Øx6' to 12'	500-1,600
Chain link fabric, 50' roll	2'Øx 6'	300-500
Lining segments and accessories	15'x5'x4'	<6,000
Shotcrete		
Wire mesh	3'Øx 6'	200-400
System Extension Materials		
Rail	30'-33' long	700-900
Ties	.4'x.6'x5'	60

TABLE 16. QUANTITY OF MATERIALS

< = less than

Maximum Material Rates as Tons per Hour

Type of Excavation and Rate of Advance / Material	Soft Ground 150 fpd 20'd	Rock: Drill-and -Shoot 250 fpd 23' d	Rock: Mole 120 fpd 20' d	Rock: Mole 240 fpd 20' d	Rock: Mole 300 fpd 20' d	Rock: Mole 600 fpd 20' d
Spare Parts	<1	<1	<1	<1	<1	<1
Electrical Supplies	<1	<1	<1	<1	<1	<1
Lubricants	<1	<1	<1	<1	<1	<1
Drill Bits & Steel	-	1	<1	<1	<1	<1
Explosives	-	1-2	-	-	-	-
Mole Cutters	-	-	<1	<1	<1	<1
Oxygen & Acet. Bottles	<1	<1	<1	<1	<1	<1
Small Tools	<1	<1	<1	<1	<1	<1
Vent Pipe						
Air & Water Pipe						
Power Cable	<1	<1	<1	<1	<1	<1
Light, Telephone & Blasting Line						
Hangers & Supports						
Sets & Access.	2	3	<1	2	3	6
Timber Lag & Block	2	<1	<1	<1	<1	2
Rock Bolts & Access.	<1	<1	<1	<1	<1	<1
Chain Link Fabric	-	-	<1	<1	<1	<1
Steel Channel Lagging						
Lining Segments & Access.	15	-	9	18	22	45
Shotcrete	-	12	6	12	15	30
Wire Mesh	-	1	<1	<1	2	4
Grout						
Conveyor Sections						
Conveyor Supports						
Conveyor Belting						
Pipeline Sections						
Pipeline Supports						
Pumps						
Rail & Accessories	<1	<1	<1	<1	<1	<1
Ties	<1	<1	<1	<1	<1	<1
Men, at shift change	10 to 20 men					

4. MATERIAL TRANSPORT SYSTEMS STATE OF THE ART

MATERIAL TRANSPORT SYSTEM TYPES

All material transport systems incorporate the following four fundamental elements.

1. A medium or vehicle to give mobility to the material.
   Examples: Belt of a conveyor, fluid in a pipeline, cars of a railroad.

2. A means of supporting the vehicle weight and the forces resulting from its movement.
   Examples: Supporting framework of a conveyor, pipe and supports of a pipeline, rail and ties of a railroad.

3. A means of propelling the medium.
   Examples: Drive pulley and motor of conveyor, pump for a pipeline, locomotive for a railroad.

4. A means of guidance for the medium.
   Examples: Supporting structure of a conveyor, pipe of a pipeline, rail and flanged wheels of a railroad

There are two major categories of material transport systems based on the flow characteristics of the material transported and the conveying medium. With a continuous flow system, the medium moves as a continuum in a closed loop and the material is continuously added to and discharged from the moving medium. In intermittent flow the transporting medium is divided into mechanical modules which divide the material into discrete units. In a confined space these modules travel along the flow path with a reciprocating motion. They may travel individually or linked together into a train. Modules or trains can be added or removed without disrupting operation of the other parts of the system; this is not a characteristic of continuous flow systems. Table 17 presents a comparison of some of the major characteristics of the continuous and intermittent categories of material transport systems.

In addition to the broad classifications of continuous or intermittent flow, material transport systems can be classified regarding their suitability for horizontal transport or elevating materials and by several other characteristics. Figure 8 shows one possible hierarchy of material transport systems. The state of development, characteristics, and potential of the various systems are discussed in Sections 5 through 9.

Intermittent Systems

Intermittent systems, most commonly represented by railroads, rubber tired vehicles, cranes and hoists, are the conventional systems usually employed for tunnel construction projects. Normally, an intermittent system

TABLE 17. COMPARISON OF MATERIAL TRANSPORT SYSTEM TYPES

Item	Continuous	Intermittent
Carrier medium	Closed loop	Modules
Medium flow	Continuous	Intermittent; reciprocating
Guideway	Closed loop	Dead end or loop
Load & discharge	Continuous	Intermittent
Power unit	Maximum initially May use boosters	Units added as needed
Materials transported	Bulk only	All
Flow direction	One way	Two way
Flow variation	Accommodate by changing speed or loading of medium. Some cases may be difficult	Accommodate by changing speed or number of modules
Guideway failure	System shutdown	System shutdown
Carrier failure	System shutdown	Remove module and continue system operation
System extension	Generally difficult	Not difficult
Space required in tunnel	Minimum - depends on average rate of flow	Generally large. Depends on module spacing and speed
Space required in heading	Depends on processing and loading equipment required	Large space for waiting modules and loading equipment
Structural suport in tunnel	Usually from wall or arch	Road bed
Automatic control	Relatively simple	Complex due to intermittent operation

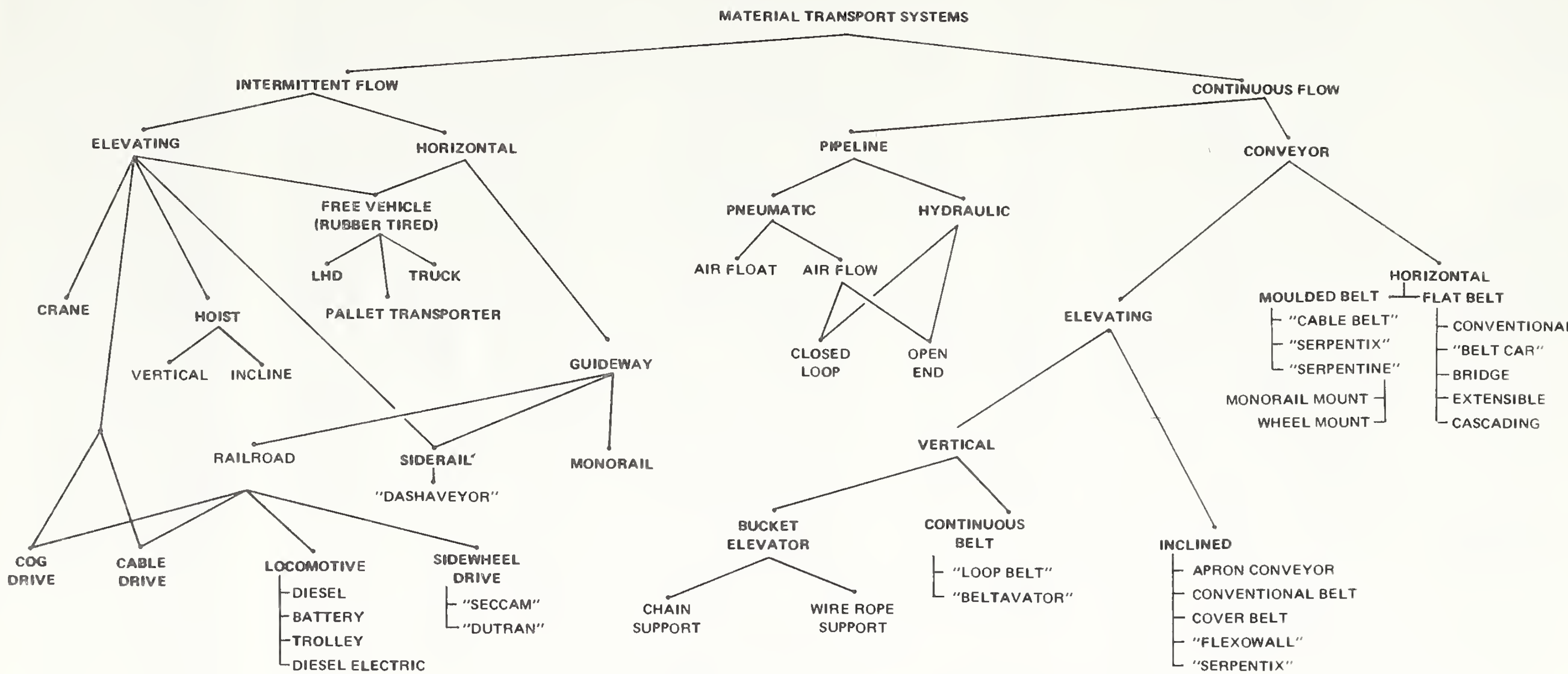

FIGURE 8. HIERARCHY OF TRANSPORT SYSTEMS

is suitable for either elevating material (crane or hoist) or horizontal transport (rubber tired vehicle or rail system), but not both. However, some rubber tired vehicles can operate on grades up to 27 percent at reduced speeds to elevate materials, and rail systems using cog drive or cable assist can operate on steep inclines. The Dashaveyor siderail system could climb vertically using a rack and pinion drive.

The conventional elevating systems (cranes and hoists) are similar in fundamental operation. A unitized load is lifted by winding a wire rope on or over a drum. The principal difference is that the hoist is stationary, moving the load along a fixed path, whereas the crane can rotate to move the load to different locations on the surface. Hoists are used to lift loads vertically in a guideway or on inclined rails. Cranes lift the load vertically, either resting against guides to prevent rotation, or hanging free at the end of the wire rope. Hoists are drum type (wire rope stored on the drum) or friction type (wire rope or ropes pass over the drum to a counterweight or counterbalancing load). Cranes always use a storage drum. Cranes can be mounted on a stationary platform or on a mobile base.

Hoists lift the load in a skip permanently attached to the hoist or by engaging the muck box in a lifting jig or cartridge. Cranes generally lift muck boxes by attaching a sling to the box.

The horizontal intermittent systems are of two major types; those that operate on a fixed guideway such as dual rail tracks, supporting rails at the sides of the vehicles, or a monorail which can be above or beneath the vehicles, and those that consist of free vehicles usually equipped with pneumatic rubber tires. Free vehicles commonly used are load-haul-dump (LHD) units and trucks. LHD units are equipped with a scoop at the front and are powered and geared for haulage runs so they perform the three functions of loading, hauling, and dumping. Trucks require an auxiliary loader. When a mole is used, the loading function can be provided by the mole and its conveyor. Specialized trucks are sometimes used for transporting and/or installing materials. A pallet transporter designed for quick loading and unloading of preassembled loads would be one type of special truck. In general, rubber tired vehicles occupy a large cross section per unit of load carried. This large size is necessary to accommodate the power plant, drive unit, controls, operator, and large tires required for each vehicle.

The most commonly used guideway system is the conventional railroad system, although monorails have been used to a limited extent in mining and tunneling particularly in Europe. In the 1960s a siderail system (the "Dashaveyor"), consisting of individually powered vehicles automatically controlled from a central location, was found to be too expensive for application in situations where the extreme versatility built into the system was not needed.

Railroad systems can be classified according to the type of propulsion system used. Most rail train systems in use employ a locomotive of some type to pull or push the train of load carrying vehicles.

A special sidewheel drive system was developed and promoted in the 1960s under the tradenames "SECCAM" and "DuTRAN" but without great success, perhaps due to the cost of distributing the drive units over the entire length of the transport path. In this system, electrically driven pneumatic tires bearing on both sides of the load carrying cars propelled the train. The spacing of the drive units is dependent on the length of the train since it should always be in contact with at least one pair of drives.

Other special drives such as linear induction motors have been proposed for rail system applications but appear to offer no advantage for underground applications. Conventional locomotives are powered by diesel engines, batteries, trolley wires, or diesel electric systems. For tunneling, trolley wires are hazardous, batteries provide insufficient speed and range, and diesel electric is expensive. Diesel locomotives are preferred, although their use significantly increases the ventilation requirements.

In general, the intermittent systems are characterized by adaptability to handle a wide variety of material sizes and shapes, to respond to wide variation in the material flow rate, and to extend in length as the transport distance increases. The horizontal systems require minimum downtime for repair since the vulnerable components can be removed from the system for repair while the system continues to operate. The vertical elevating systems do not have this advantage since breakdown of the crane or hoist mechanism will shut down the system.

The biggest disadvantage of the intermittent systems is the large cross-sectional area requirement caused by "lumping" the bulk material into modules or discrete units. This problem becomes most significant when the material flow rate becomes great enough to require passing of loaded and empty carriers in a narrow passageway. The problem becomes particularly acute in elevating when each load module must be lifted separately. The intermittent traffic also tends to increase the safety hazard.

Continuous Systems

The cross-sectional area of continuous flow systems can be smaller than for intermittent systems because the payload covers the entire length of the flow path and is discharged constantly from the carrier medium. However, the continuous systems, particularly pipelines, are more likely to require size reduction and separation of muck, thus requiring large equipment in the heading, where space is at a premium.

Two basic types of continuous flow systems are used: those with a fluid medium in a pipeline and those with looped belt or chain propelled by a rotating drum or sprocket wheel.

The pipeline systems employ either low pressure compressed air or water as the carrier medium. Either system (air or water) can operate as a closed loop or an open ended pipe system, although most of those in use are open ended to save the cost of the return pipeline. The technical feasibility and economic advantage of both these system types is well proven in specific commercial applications; for example, overland hydraulic systems for transport of coal and minerals, and pneumatic systems for low density or finely pulverized materials.

The air float pneumatic system diffuses air through a porous plate, longitudinally bisecting a pipe or duct, to fluidize a pulverized material on top of the plate. This material then flows down the incline of the duct by gravity.

One advantage of pipeline systems is that they are suitable for either horizontal or vertical transport of materials. Also they occupy relatively small cross sections along the transport path, but equipment at either end of the pipeline, for loading and unloading the system may be quite large. Pipeline systems, particularly hydraulic, tend to be difficult to extend on a continuing basis. Although overland hydraulic systems and most commercial pneumatic systems for bulk material are open ended (picking up the carrier medium at one end of the pipeline and leaving it at the other end), these systems, particularly hydraulic, when applied to tunneling would be closed loop, thus increasing the capital cost.

Conveyors are characterized by a mechanical carrier medium, such as a belt or chain, moving continuously in a closed loop. The bulk material may be loaded onto the carrier as a continuous ribbon or as discrete units in carrier pockets. In either case, the material is fed to and discharged from the system continuously and automatically. Conveyors can be divided into two groups, those suitable for elevating materials and those suitable for horizontal transport. Some conveyors suitable for elevating materials can also be used for horizontal transport, but are economically limited to short distances.

Horizontal conveyors are usually based on flat belts driven by one or more powered drive pulleys and troughed by idler pulleys to increase the load capacity. Exceptions are the systems based on molded belts developed for specific applications. For example, the "cable belt" with molded ridges along the length of the belt at the edges, was developed to increase the single flight distance of overland conveyors. This belt rides on cables which carry the driving tension of the system. The "Serpentix" and "Serpentine" belts have molded convolutions at the edges and are driven at the centerline of the belt which enables them to negotiate horizontal curves.

Flat belt conveyors have been used in thousands of commercial applications for many years and have seen many improvements in design and manufacture of the belting and other components of the system. The "belt car" is a recent innovation to increase the lump size which can be handled and the capacity of the system. In this system, moving "cars" give support to the belt while under load thus giving it the ability to handle enormous lumps and carry very large loads. Bridge conveyors can span long distances and be supported on pivot points at the ends to provide flexibility. Extensible conveyors use a "belt bank" to store several hundred feet of belt which can be extended into the length of the system without shutdown for belt

addition. Cascading systems were developed to provide extreme flexibility and mobility in the system. Most of them proved to be too expensive for commercial use.

Material can be elevated by lifting vertically or by moving up an incline. Conventional flat belt conveyors can elevate materials on inclines up to 15-18 degrees. By placing a cover belt over the material on a conventional belt, the angle of incline can be increased to about 45 degrees. The "Serpentix," because of its convoluted pockets and ability to negotiate curves, can spiral upward around a fairly small cylinder diameter and carry a reasonable load. The "Flexowall" conveyor obtains larger load capacity on inclines by attaching fluted sidewall and cross-belt cleats to the belt. An apron conveyor, consisting of linked metal pans mounted on wheels which travel on a horizontal or inclined dual rail track, has particular advantage when handling materials at elevated temperatures.

The conventional conveyor for vertical lifting is the bucket elevator, usually with metal buckets attached to continuous chains driven by sprocket wheels. There are bucket elevators that have the buckets attached to a belt, but these are usually limited to relatively small loads. Wire rope supported and driven bucket elevators have been developed, and at least one concept has been successful in unloading free flowing granular materials from shipholds and stockpiles. This concept has a series of heavy duty buckets strung on a wire rope passing through the center of the buckets. Special pulleys have been developed to allow the string of buckets to move through almost any path desired. Other less successful vertical elevating concepts have been based on the Ferris wheel principle to engage and lift muck boxes to the surface. The capacity and height of bucket elevators is limited by practical speeds of travel and the load that can be placed on the supporting chain or wire rope.

Flat belts also have been used for elevating materials vertically by making use of the cover belt principle. The most established example is the "Loop Belt" used to unload bulk cargo from Great Lakes ships. By covering the load on the carrier belt with another belt traveling at the same speed it is possible to transport the material in a long-radius arc to elevate it from the bottom of a ship's hold. The "Beltavator" is a more recent modification of the "Loop Belt" principle which allows material to be elevated on a vertical line between two flat belts.

In summary, there is a very wide variety of material transport systems and the variations of detail within a type of system make the specific examples almost limitless. As the various basic types are modified in details, they begin to take on the characteristics of other types and differentiation becomes difficult. For example, a sidewheel drive train can be visualized which becomes small in cross section but so long it closes on itself to become a continuous loop, hence an enlarged apron conveyor.

All the systems identified in Figure 8 have been shown to be physically feasible and many have been proven to be the most economical choice for particular applications. Others have failed to find an economical application and appear to have fallen by the wayside. However, just because a system has been accepted as the best economic choice for a particular application does not mean that it will necessarily be economically competitive in another situation such as tunneling.

The conventional systems presently used in tunneling are found in the intermittent group of systems, but there may be continuous flow systems which offer advantages and are economically competitive with the conventional systems, particularly for elevating materials. One major disadvantage of continuous systems which it is difficult to overcome, particularly for horizontal haulage, is the fact that the continuous systems can transport only the bulk materials (muck) in a tunneling operation.

AUXILIARY EQUIPMENT

The auxiliary equipment required by the material transport system is determined by the type of excavation equipment and the materials transport system used. In comparing material transport systems, the auxiliary equipment required by each material transport system must be included in order to obtain a valid cost comparison. Loaders, processors, transfer units, movers, unloaders and surge storage units are the usual types of auxiliary equipment.

Loaders

In soft ground, hand-mined tunnels, 1/4 cy overshot loaders are used to charge rail cars directly or charge a conveyor belt which in turn loads the cars. Alternatively, on short tunnels, load-haul-dump (LHD) units excavate the face directly and tram the muck out of the tunnel. With drill-and-shoot excavation in hard rock, 2-1/2 to 5 cy front end loaders, often with side dump or ejector buckets, are used to load trucks. On longer tunnels, a Conway overshot loader, 3/4 to 1-1/4 cy capacity, is used to charge muck cars. In mole excavated tunnels, the excavating mechanism places the muck on a conveyor which in turn charges the rail mounted muck cars directly, or charges a long trailing conveyor that in turn loads the muck cars.

To load muck into a hydraulic transport system, an extensible conveyor or a pneumatic system would be used to reach to the pipeline loader. Muck mixed with water can be fed directly into the pump or can be injected directly into the pipeline with a lock hopper. To load a pneumatic system, muck is fed into a rotary valve that drops the material into the air stream. A conveyor could be loaded directly from the mole conveyor or from a feeder conveyor if size reduction is required before loading the conveyor.

Passers

Passing of muck cars at the heading is critical and various methods, all using long passing tracks, are used. The ability to pass haul units is required when more than one haul unit is used. Circular tunnels in soft ground supported with segments preclude excavation of widenings for passing.

Therefore, they require narrow equipment to permit passing. Solutions to the passing problem are the use of a "car passer" to shift the empty rail car to one side and allow the loaded car to pass, or to provide a conveyor that spans over enough cars to load the muck from an entire shove of the shield. The muck train is then removed and dumped while the segment ring is erected. This may require passing a waiting empty train on a "California switch," which is two parallel tracks on wheels that can be jacked up, moved ahead, lowered, and blocked into place, so as to advance with the heading. Another solution is to use a "cherry-picker" hoist to lift an empty muck car allowing the loaded car to pass underneath. Passing is provided by widening drill-and-shoot tunnels in ground competent enough to allow the overexcavation. Car-passers or parallel passing tracks are placed in the widening. With truck haul, empty trucks pull into the widenings and wait for the loaded truck to pass. In long, wide drill-and-shoot tunnels train passing is provided with a California switch or a "Jacobs floor," a series of heavy steel plate-bottomed panels with passing tracks mounted on top that are hydraulically shoved forward as the heading is advanced.

Processors

Processors include grizzlies or scalpers to remove oversize muck and crushers to reduce the muck size. Processors are not required with rail or truck haulage. Conveyors that load rail cars are sized with minimal concern for manufacturers recommendations regarding lump size. Vertical conveyors generally require scalpers to insure that no oversize material which may cause damage is fed into the system. Pneumatic systems used with moles require only scalping to remove oversize, whereas hydraulic systems require that the muck is crushed to less than 5/8". Equipment must be provided to transport the scalped oversize material, or it must be crushed down to acceptable size. Underground processing generally has been limited to mining operations; however, a recent sewer tunnel job in Chicago was designed with a grizzly and crusher preceding the feed to an inclined conveyor, and a job in Washington, D.C. had a grizzly between the rail car dump and the belt feeder to a bucket elevator. It is economical to install underground primary crushing facilities to minimize transfer problems and reduce equipment wear if the material will ultimately be crushed anyway. The tunnel industry has had no requirement for ultimate size reduction of muck, so it is more economical to design the haulage equipment to minimize the transfer problems and accept the wear caused by large material size. Crushers sized for 900 tph are too big to fit conveniently into a 20' tunnel.

Transfer Equipment

The most extensive transfer equipment occurs at the point of horizontal to vertical muck transfer. Usually, surge storage facilities are included. Other common transfer points are from the excavating to hauling equipment and from surface storage to trucks for haul to final disposal. Transfer equipment consists primarily of conveyors, various type of feeders, and chutes.

Movers

Rail cars are often moved with cable drive mechanisms or hydraulic cylinders at loading and unloading points to reduce equipment investment, congestion, ventilation, and manpower.

Unloaders

There are two types of unloaders: those mounted on the haul equipment and those with fixed mountings, usually over a storage facility or feeder. Examples of unloaders mounted on the haul unit are ejector buckets on front end loaders and air operated dump mechanisms in rail cars. Stationary unloaders are hydraulic cylinders to tip side dump cars, tippers for rotary dump cars, scrolls for bottom dump cars, belt trippers, settling ponds and classifiers for hydraulic systems, and cyclones and hydroclones for pneumatic and hydraulic systems.

Surge Storage Units

Surge storage is desirable at all transfers between haulage modes (mole to rail car, hoist to truck, rail car to hoist, mole to slurry feeder). It is typically provided between the horizontal and vertical material transport equipment. Storage between intermittent and continuous haul modes is required to provide a smooth feed rate to the continuous mode. It is normal for front end loaders to tram muck back and store it along the ribs when there are no trucks to load. Recent innovations in surge storage are several applications of hopper bottom units at the heading which quickly discharge into haul units, the idea being to reduce the number of haul units and give better haul unit utilization.

RESEARCH, DEVELOPMENT, AND DEMONSTRATION PROGRAMS

BuMines Program

One of the most extensive coordinated research and development programs for bulk materials handling is that of the U.S. Bureau of Mines. This program was initiated in response to the Coal Mine Health and Safety Act of 1969 which mandated further exploration in the area of coal mine haulage. Initially, the program surveyed bulk material handling concepts to identify novel approaches which might have application to coal mine haulage. These early investigations (41) included feasibility studies of systems such as hydraulic pipeline and pneumatic conveyance which had been proven practical for surface applications, and investigation of other concepts such as the siderail (Dashaveyor) and sidewheel (SECCAM or DuTRAN) for which demonstration units had been built and tested by equipment manufacturers. In addition, less developed ideas were looked at and test models built for some of them. For example, pilot scale tests were conducted at the Pittsburgh laboratory on a heavy-media hoist, a peristaltic conveyor, and an undulatory conveyor. Other ideas, such as the Rolamite concept, the Archimedes' screw, and a conventional conveyor belt suspended on an air cushion and driven by a linear induction motor, were not investigated beyond the concept stage due to the apparent impracticality of the concept for coal haulage.

The undulatory conveyor was thoroughly tested and the results reported (42). The idea was abandoned due to impractically low capacity and high power costs. Only 18 percent of the material within an undulating wave was moved forward with a wave cycle, giving a capacity of 66 tons of limestone per hour for the 48-inch-wide model. In contrast, a conventional belt conveyor of this width could carry well over a thousand tons per hour. The full-size model required 22 horsepower-hours per ton-mile contrasted to 0.22 horsepower-hour per ton-mile for conventional belt systems.

Investigation led to the conclusion that the peristaltic principle is not practical or economical for a bulk materials transportation system; however, work is continuing on application of this principle in a feeding device for other transport systems.

The heavy-media hoist appears impractical as a device for elevating dense materials due to the large pressures required to inject material into the device at the bottom of the heavy-media column. If a heavy medium could be found to give a reasonable rate of rise for the bulk material, the injection pressure required would probably be greater than the pressure required to elevate the material by pumping in a hydraulic system, and the capacity of the heavy-media pipe would probably be much less than an equal size hydraulic pipe system.

The sidewheel concept, originally developed in France as the SECCAM, was licensed by Dravo Corporation and marketed as the DuTRAN. However, after several years of no interest from potential users, the license was dropped and marketing efforts ceased. The siderail system, originally developed by the Dashaveyor Corporation for hauling mined ore, was found to be complex and expensive due, at least in part, to the high degree of flexibility designed into the system. Neither of these concepts is presently a part of the active program of the Bureau of Mines.

The Bureau of Mines' present materials handling program is directed primarily toward the development of more efficient transport of coal from the excavation face to the preparation plant with emphasis on face haulage by specialized conveyors (43). The approach emphasizes improvement of design, adaptation to special problems, and demonstration of systems proven to be practical in coal mine use or other applications rather than development of novel concepts. Projects are conducted either in-house or through contracts with industry or universities.

The most common means of face haulage in U.S. underground coal mines is by shuttle cars. However, their safe load capacity of about 10 tons limits the production rate when they are placed between a continuous mining machine capable of producing about 600 tph and secondary and main haulage systems which can carry several thousand tons per hour. Projects to improve shuttle car performance include development of larger capacity shuttle cars, cableless wire-guided automated systems, and diesel fueled steam powered engines as an alternative to electric trailing cables, batteries, or diesel engines.

Many U.S. coal mines have used conveyors for continuous face haulage for many years. The two most common types are the bridge conveyor (either belt type or chain type) with mobile carriers and the extensible belt conveyor.

The application of extensible belt conveyors apparently peaked in the 1960s and then declined. Flexible conveyor belts, capable of operating around short radius curves, have been developed but have seen very limited use. These flexible belt systems are available under two trade names, the Serpentix and the Flexible Conveyor Train. The longwall conveyor system, which is used in many longwall mining operations, is a combination of an armored drag-chain face conveyor, a transfer conveyor, and an extensible belt panel conveyor. It is not suitable for conventional or continuous room-and-pillar mining. Cascading conveyor systems have been developed under the tradenames Moleveyor and Mineveyor, but have not been accepted by industry due to their high cost.

Major objectives in the development of face haulage conveyor systems are:

a. To increase the haulage capability to match the 600 tph production rate of presently available coal extraction machinery.

b. To provide the mobility required for working of several excavation faces.

c. To develop low-profile equipment suitable for continuous face haulage in coal seam thicknesses down to 42 to 30 inches.

Several projects sponsored by the Bureau of Mines have been initiated in recent years to achieve these objectives. Among these projects are:

a. A high capacity bridge conveyor with mobile carriers suitable for 90 degree turns in narrow entries.

b. A 500-foot long, single flight, mobile Flexible Conveyor Train operating on a roof mounted monorail, with the ability to carry 600 tph through 90-degree turns.

c. An auto-track Bridge Conveyor Train with a wireguided automatic control system capable of 500-foot haulage at 600 tph.

d. A multiple-unit cascading continuous haulage system consisting of eleven self propelled, four-wheel-steerable cars with a conveyor on each. The objective is to develop an improved version of the Moleveyor in response to renewed interest in the concept.

e. A bendable belt conveyor to negotiate a 90-degree curve using a conveyor type belt and a series of self-tracking carts to support the conveyor belt apparatus.

f. A monorail, roof-mounted Serpentix conveyor with reduced profile capable of moving 600 tph (rather than 370 tph present capacity) in the coal seams.

g. An articulated chain conveyor suitable for use on a shortwall face to feed a mobile conveyor in the head gate.

h. A longwall face conveyor capable of moving 1,000 tph with surges up to 20 tph.

i. A conveyor belt extender apparatus capable of extending or retracting a belt conveyor 100 feet in 15 minutes.

j. A conveyor belt transfer point design to operate in low headroom with high belt speed and change of direction while providing low spillage and reduced wear and dusting.

k. A study of belt tracking forces to provide better understanding of belt training and the tendency of belts to wander transversely on the idlers.

l. Development of a belt cleaning system to minimize maintenance and return fines to the belt payload.

An evaluation (19) of continuous face haulage concepts to select those concepts with the highest potential for practical application placed the rail hung Flexible Conveyor Train at the top of the list. It was, in fact, the only concept receiving an overall rating higher than the shuttle car system when evaluated on the following eleven points:

1. Capacity, steady state

2. Capacity, surge flow

3. Ability to handle large pieces

4. Spillage and carryback

5. Advance-retract speed

6. Traction

7. Ability to convey around corners

8. Reach capability

9. Inherent safety

10. Dust generation

11. Noise generation

The most common method used for main haulage in underground coal mines is a locomotive powered train of open cars on a dual rail system. A project to design and demonstrate an automated rail haulage system in a normal production mode is part of the Bureau of Mines program. Other projects to improve rail haulage include an evaluation of the feasibility and effectiveness of compacting the load in a mine car by induced vibration and evaluation of internal combustion engine concepts for mine locomotives to improve maintenance operations, minimize toxic emissions, and reduce the engine profile.

Another approach considered for secondary and main haulage is the use of pipelines with a fluid medium to transport the coal. The pneumatic system (either pressure or vacuum) is no longer a part of the Bureau of Mines program due to high cost and other inherent disadvantages considered serious (41). The hydraulic concept which has been used with success for overland transport of coal was studied in 1-inch, 3-inch, and 6-inch pipe systems and found to offer enough promise to justify tests at greater than 2,000 tph of coal in 6-inch, 12-inch, and 18-inch pipe loops which are now under construction (completion early in 1979) at the Bruceton, Pennsylvania Bureau of Mines research center. These tests will provide engineering data and test pumps, drives, injectors, controls, concentrators, sensors and separators. Another project has been established in the slurry program to develop a low-profile feeder for injecting coal directly into the pressurized pipeline so it will not pass through the pump.

A project also is underway to develop a hopper-feeder and spillage-cleaner machine to work between the continuous miner and haulage system. This machine would provide the functions of surge hopper, feeder, breaker, tractive vehicle for the haulage system, loader to clean up spillage, rock dusting, roof bolting, and extending the ventilation system.

UMTA Program

The Urban Mass Transportation Administration of the U.S. Department of Transportation has supported for several years a program in materials handling directed to the development of more efficient methods of materials transport during tunnel construction. The program has included survey study of alternative methods of material handling to identify and evaluate the potential for application to tunnel construction. It has focussed on the transport and utilization of muck. For example, projects have included:

a. Materials handling systems studies.

b. Verification tests with a pneumatic system in the range of 50 to 100 tph of quarry rock.

c. Studies of transportation of muck by hydraulic pipeline.

d. Evaluation of hydraulic transport and solids separation applied to excavation in sandstone.

e. A survey of potential uses of tunnel muck.

f. A study of the potential for savings by coordination of the excavation schedule with needs for bulk material.

The materials handling systems studies have included:

a. a survey and systems analysis (21) of alternative material transport methods for tunneling under assumed conditions of extremely rapid advance rates in very long tunnels at great depth envisioned for interurban underground transport of the future,

b. the present study which investigates alternative material transport methods for rock tunneling under conditions projected to the year 2000 for urban mass transit system tunnel construction.

The verification tests (27) with a pneumatic system were performed to evaluate the following system operating features:

a. Wear and maintenance requirements (in pipeline, crusher, and feeder).

b. Pipeline extensibility to simulate operation behind a tunnel boring machine.

c. Effect of particle size distribution and moisture content on system performance.

d. System energy requirements and operating costs.

e. Throughput capacity of the system.

f. Noise and dust levels.

g. Reliability and flexibility of the system.

These tests have given encouraging results, especially for vertical transport of muck-like materials.

The studies of transportation of muck by hydraulic pipeline have been completed (24, 28). The objective of these studies was to advance the state of muck haulage by slurry pipeline through analysis of crushing equipment, extensible conveyors, hydraulic slurry head loss data, and slurry dewatering systems. The final report (28) provides information on:

a. Muck quantities and characteristics projected for the future.

b. Equipment for muck preparation (crushing) to provide the desired particle size distribution.

c. Extensible conveyor systems to serve as an extendable link between the tunnel boring machine and the pipeline feed unit.

d. Power requirements for coarse slurries.

e. Jet pumps for slurry transport.

f. Equations for pneumatic pipeline calculations.

g. Calculations and costs for slurry dewatering systems.

The evaluation of hydraulic transport and solids separation (54, 58) was performed for a system in use for excavation of tunnels in St. Peter sandstone. The study documented performance and costs of hydraulic excavation and materials handling under actual construction conditions. Muck characteristics pertinent to solids-water separation were studied at the laboratory and pilot plant scale using actual tunnel muck. A prototype optimized muck treatment system was designed and its operation monitored at a hydraulic-mining tunnel construction project.

The studies of muck utilization have as their objective the reduction of tunneling cost by converting a waste product (muck) into a resource of value thus reducing or eliminating the muck disposal cost by providing income to the contractor or owner. An extensive study (48) of muck utilization including guidelines for muck utilization planning, was performed and a trial case study was applied to the Baltimore Rapid Transit System. Another study investigated the potential savings if tunnel construction projects were undertaken during periods of high demand for bulk materials which might be satisfied by the muck produced by the tunnel construction.

Industry Research and Development

Industry in the United States generally has taken a conservative approach to research and development in the field of materials handling. The objective of programs funded by equipment manufacturers is usually product improvement rather than basic research or development of new concepts. Equipment manufacturers can justify the expense of research or full scale demonstration of new products only if a potential market of significant size and duration is seen. During discussions with manufacturers this point was expressed in several ways, such as:

a. Development will keep up with the needs if the market is big enough.

b. Manufacturers need to know what the market will be before they are willing to develop the equipment.

c. The only justification for the expense of research is a future sales potential. There must be reliable projections showing a long term and continuous market.

d. Manufacturers cannot make a significant investment to save money for contractors or owners unless there are sufficient potential sales to return the investment to the manufacturer.

Fortunately, equipment improvements and system developments required to meet the needs of one segment of industry provide improved equipment and systems for other applications as well. The market potential can be assessed for industry in general rather than for any single area of application. Therefore, the major equipment manufacturers have continuing development programs to maintain or improve their competitive position in the market. For example, Rexnord has the largest chain test and development

operation in the industry and has developed chain with load capability beyond identified industrial requirements for bucket elevators. They also have built and tested at full scale an experimental cement elevator instrumented with photographic and other diagnostic equipment, and have developed designs for intermediate drives for bucket elevators.

The Bucyrus-Erie Company feels that because of continuing engineering development, the crane industry keeps up with the need and has the technology now to provide lifting equipment to handle the muck rates projected for the 1990 period.

The most notable innovations in material handling systems developed by equipment manufacturers in recent years have been for belt conveyors. These new approaches, which often have been developed by belt manufacturers and equipment manufacturers working together, have included:

a. Improved belt designs reinforced with steel for higher belt tension permitting longer flights and faster speed.

b. Convoluted belts to permit travel around short radius curves.

c. Vertical sidewall belts and covered belts to permit steeper angles of incline.

d. Wire rope supports to reduce cost and installation problems.

e. Traveling belt supports to permit handling very large lumps up to 60 inches.

f. Double belts which permit lifting on an arc or on a vertical line.

g. Jointed belt supports which hold promise for travel around long radius curves with conventional belts.

h. Intermediate drives of various designs to permit flights of any desired length.

Stephens-Adamson maintains the most extensive research facility for belt conveyor systems in North America at its Ontario manufacturing facility. It includes full scale test loops for a Loop-Belt conveyor, a Beltavator and a 48-inch high-speed belt operating at up to 2,600 feet per minute. More than one manyear per year is devoted to pure research for product improvement without an identified market for the improved product. For example, the Beltavator was developed with government grants covering about 50 percent of the cost before a customer was identified.

Tunnel construction contractors must be cautious in the application of new techniques on fixed price jobs. They cannot be innovators to the extent of adding substantial risk to an already high risk business venture. Before they can accept the risk of introducing new technology to a job, there must be a high level of assurance that the new technology will not impose additional delays on job progress. This assurance can be obtained only by demonstration of the capability and reliability of new systems in an environment comparable with that found in tunnel construction. The incentive

for innovation by contractors is small. Even if the new technology is highly successful, the financial advantage gained is limited to the initial job as there is widespread technical information interchange among tunnel contractors. Any long-term financial gain is soon passed on to the owner through the process of competitive bidding.

In spite of the financial risk, some tunnel contractors have tried new approaches in an attempt to improve muck haulage or hoisting. Early installations of a slurry system and a conveyor system encountered technical difficulties and were abandoned. These difficulties were, perhaps, due to the systems being installed in a full scale production environment before they were fully developed, or to inadequate engineering of the systems to meet the severe requirements of tunnel construction.

More recently, bucket elevators have been installed for muck hoisting on jobs in Maryland and Illinois by the James McHugh Construction Company and an inclined conveyor has been installed by a joint venture of Kenney-Paschen-S&M to lift muck to the surface from two headings being worked simultaneously for the Chicago Metropolitan Sanitary District. Although these installations are based on equipment which has been proven in other applications, they have presented problems to the contractors when confronted with the highly variable conditions typical of tunnel construction.

Owners and operators of mining properties have justification for investment in material handling innovations if they can show by cost analysis a good prospect for reduced haulage cost. The investment cost will be recovered and reduced production cost realized over the long life of the mining operation. However, operators generally do not employ the engineering staff or have the facilities for major equipment development so their activities in material handling system development usually consist of test and demonstration of systems developed in conjunction with one or more equipment manufacturers with the operator providing requirements specifications, materials properties, system design, testing, and evaluation of performance.

A good example of this approach is the development by Consolidation Coal Company, a subsidiary of Continental Oil Company, of a slurry pipeline system for conveyance of coal from the mine face to the preparation plant. After seven years of research, design, testing, and pilot operation, a full-scale hydraulic transportation system is being installed to transport coarse coal at their Loveridge Mine beginning in May, 1978 (15). The system will:

a. follow the mining machines,

b. receive lumps of coal as large as twelve inches at the mining faces and at rates comparable to mining machine capabilities,

c. reduce the large lumps to four inches,

d. produce slurries with 4-inch top particle size,

e. pump these slurries through feeder lines,

f. combine and concentrate the coarse slurries from several faces,

g. pump the combined slurries vertically about 900 feet to the surface and 2.4 miles overland to a water separation facility at the preparation plant.

Other examples of full scale demonstration by mining operators of system innovations developed in conjunction with equipment suppliers are an intermediate drive concept for belt conveyors developed jointly by B. F. Goodrich and Continental Conveyor Company and installed at an American Cyanamid Corporation open pit phosphate mine in Florida and in the underground York Canyon coal mine of Kaiser Steel in New Mexico.

ENVIRONMENTAL CONSIDERATIONS

Three recent studies have addressed different aspects of the environmental impact of the tunneling process. Wolff and Scholnick (89, 90) assessed the disruptive effects on the social, economic, and physical environment with particular emphasis on cut-and-cover urban tunneling. Li, et al (48) studied potential uses of tunnel muck to convert it from an adverse impact to a benefit.

When viewed in the overall context of the urban transportation tunneling process, the environmental impacts on the public of underground tunnel construction using tunnel boring machines are considerably less than those resulting from cut-and-cover or drill-and-shoot construction techniques. For moled tunnels most of the impacts on the public are related to the surface transport of materials to and from the job. In nearly all cases, this material transport is by truck.

The major adverse impacts are noise, traffic congestion, dirt, and visual impact. The visual impact of the construction yard and truck loading equipment can be mitigated to some degree by the use of fencing and screens, but these are of little value if their appearance, due to poor design, construction, or maintenance, is as unsightly as that which they are trying to hide. There is little that can be done to hide a crane operating on the surface or trucks moving through the streets. Reducing the number of trucks might be considered by some observers to be an improvement, but if the same material flow is to be maintained, the trucks become bigger, which is less desirable in traffic.

Noise might be mitigated somewhat by the use of improved mufflers and sound shields on trucks and equipment operating in the yard and at the shaft. However, a goal of no increase in noise level in the vicinity of the construction yard and shaft is not practical.

The adverse impact of dirt can be mitigated by care in handling materials, particularly muck. Reductions of dust and spillage are of major concern.

The major source of traffic congestion would be eliminated if the muck trucks could be removed from the streets. It would seem that substitution of a continuous transport system such as conveyor or pipeline might offer a solution. But when the problem of street crossings is considered, it

becomes apparent that this would be a case of substitution of one adverse impact for another. The appearance and inconveniences of a conveyor or pipeline running above the surface along the street or sidewalk and elevating for clearance at street crossings would most likely be unacceptable to the public. To bury a continuous system would be prohibitively costly and disruptive.

It appears that improvements in the environmental impacts resulting from materials transport for urban tunneling are more likely to be found in careful planning and execution of the project than in selection of alternative material transport systems. For example, placing access to a tunnel segment as close to the muck disposal site as practical would contribute to reduction of traffic problems.

5. CONVENTIONAL SYSTEMS

The materials handling system used almost universally by tunnel construction contractors, when excavating with a tunnel boring machine, consists of a dual-rail train operating in the invert between the heading and shaft (or portal), a crane or hoist for elevating through the shaft, and pneumatic tire trucks for surface transport. Rubber tire vehicles are also used during development excavation or for short-reach tunnels where use of a tunnel boring machine is not feasible.

An advantage of a rail haulage system over other possibilities is that a train hauls everything; supports, muck, people, supplies, and equipment. Thus it would seem that if a rail system is to be installed to transport the incoming materials which are not suitable for transport by a continuous system, muck could be transported by the rail system with only the added cost of the additional rolling stock required for muck haulage. However, a rail system for muck haulage also has the added costs of the loading and unloading equipment, increased ventilation capacity, switches for passing trains, and additional excavation for the unloading station.

RAIL HAULAGE

Although all rail haulage uses the same basic system consisting of conventional rails attached to cross ties (or a concrete invert if precast concrete segments are used for initial lining), a locomotive driven train, and loading and unloading mechanisms at the ends of the haulage path, there is considerable variety in the details of the systems used. For example:

a. The weight of rails used may vary from less than 40 pounds per yard to 100 pounds per yard.

b. Cross ties may be wood or steel, or the rails may be anchored directly to the concrete invert.

c. The rail gage may be from 24 to 42 inches.

d. The railbed may be ballasted or unballasted.

e. The locomotive weight is from 6 to 45 tons, most frequently in the range of 15 to 25 tons.

f. Muck cars range from 4 cubic yards to 25 cubic yards capacity, most frequently in the range of 10 to 17 cubic yards.

g. Cars per train vary from 4 to 9.

h. Maximum rate of travel varies from less than 6 mph to more than 15 mph.

i. System capacities range from less than 300 tph up to 800 tph.

j. Unloading may be by side dump, rotary dump, or lift off box elevated to the surface and dumped on a muck pile.

The trend, as tunnel boring machine advance rates increase, is toward larger locomotives and muck cars, with more cars per train traveling at higher speed to increase the capacity of the system. This requires heavier rail and improved installation and maintenance of the roadbed.

System Capacity

In a series of interviews with contractors, designers, and manufacturers conducted by Holmes & Narver, Inc. (33), one area of general agreement was that the capacity of rail haulage systems, in tunnels larger than 15 feet in diameter, can be increased to keep pace with the demands of tunnel boring machines. This is in contrast to statements previously published which indicated that the rail haulage system was or might become a constraint on the rate of advance achievable by the tunneling system. Typical comments heard during the interviews include:

a. The idea that rail haulage is a restraint to tunneling progress is a myth. Rail haulage will always keep up with the heading advance. Tunnel haulage railroads are built only to suffice. As better railroads are needed, contractors will build them.

b. Many contractors do not use the full capability of the rail system. This gives the false impression that rail haulage cannot keep up with the excavation progress.

c. As the muck rate increases, all that is required is bigger muck cars and bigger locomotives. The bigger cars will require more massive dumping equipment and the bigger locomotives require more ventilation in the tunnel.

d. In a 14.5-foot diameter tunnel, over 500 tph of muck were hauled using five trains with 6t locomotives, four passing tracks, and 4 cy lift-off boxes being hoisted 60 feet to the surface. Lifting muck and lowering ground support materials through the shaft were the controlling factors.

e. A rail system using a 25 ton locomotive can easily handle 800 tph in a 19-foot tunnel.

f. Double tracking the main line is not the answer to increased capacity. Passing tracks will do the job.

g. Double tracked railroads are not required and are not economical.

h. If haulage becomes a problem, more trains can be added to the system by adding more passing tracks at closer intervals.

i. Adding trains to the rail haulage system means more switches and more passing track. The train must slow down to go through the switch and must wait on the passing track.

j. Add more trains as required to keep up with the mole production. Double track the main line if required.

k. The Stillwater tunnel is being set up with passing tracks at 12,000-foot intervals to provide no-delay haulage for 36,000 feet.

l. On this 21-foot diameter job, the haulage system which was designed for an 18-foot tunnel has no difficulty handling the maximum muck rate since the tunnel is at shallow depth so hoisting is not a constraint.

m. I cannot foresee advance rates that bigger trains could not handle. Trains can keep up with the horizontal muck haulage requirements.

Derailment

The major problem indicated for rail haulage systems during the Holmes & Narver interviews (33) was derailment. Many causes of derailment were identified, including:

a. Improperly designed, installed, and/or maintained rail and roadbed.

b. Poor quality rolling stock.

c. Improperly designed or installed climber points to the trailing floor.

d. Improperly selected, installed, or operated switches.

e. Use of dead axles causing wheel flanges to bear excessively against the rails resulting in rail spreading, flange climbing and derailment.

f. Excessive speed.

It is generally agreed that to achieve higher speeds and less downtime, track installation and maintenance of higher quality than is often the present practice is required. The limited time available for installation of track and the desire to reduce capital expenditure were given as factors affecting present track quality. Better quality trackage has been obtained by rebuilding the track behind the trailing floor. In this approach, the short segments (about 10 feet) of track laid directly behind the mole but in front of the trailing floor are removed and replaced with greater care by longer track segments (about 30 feet) about 500 to 1000 feet behind the trailing floor.

A practical goal for train speed is often stated between 17 and 25 mph, rather than the 10-mph limit dictated by many present day systems. The highest possible safe speed is desired to reduce the number of trains required, particularly for long hauls.

A factor contributing to the quality of the rolling stock is the use of a short wheel base on the locomotive. This causes "kicking" on curves and rocking on straight runs. Either of these can cause excessive wear and derailment of cars. One factor was identified as car suspension which is either too flexible or too inflexible. Eight-wheel locomotives and cars are

superior to 4-wheel for negotiating curves and switches particularly as the size of cars and trains increases. Some comments heard regarding derailment are:

a. You cannot haul muck any cheaper than by rail but you need good rail. The rolling stock must stay on the rail.

b. The climber points to the trailing floor are the major cause of derailment.

c. Derailing at the entry to the sliding floor and switches can be eliminated by proper installation.

d. Ninety percent of the derailments could be prevented by spending the time and money to get and use better equipment.

e. The switches used are often too short.

f. The most important consideration in rail haulage is properly designed and installed rails, ballast, and sub-base, including adequate drainage to keep water out of the ballast and base.

g. A preventive maintenance program is essential to keep a rail system operating but derailments are a fact of life and must be lived with. Maintenance should not wait until it becomes "breakdown maintenance." A track man who patrols the haulage rail to detect misalignments and faults is a good investment.

Live Axle Versus Dead Axle

All rolling stock used on standard railroads for overland transport of passengers and freight has live axles; that is, the wheels are attached rigidly in pairs to a connecting axle which rotates in bearings at both ends. With this arrangement, both wheels attached to an axle rotate at the same rate and describe the same path length. When traveling on a curved path, the wheel on the outside of the curve must travel further than the inside wheel. To compensate for this requirement and reduce slippage between the wheel and the rail, the wheel tread that contacts the rail is tapered so that the wheel diameter is larger at the inside edge next to the flange than it is at the outside edge. Thus, as the axle assembly travels on the curve, it moves toward the outside of the curve resulting in an increase of contact diameter for the outer wheel and a decrease of contact diameter for the inner wheel. If the proper wheel diameter and taper are selected for the track gage and curve radius the wheel assembly can traverse the curve without wheel slippage. Larger diameter wheels or less taper can be used for longer radius curves. On a straight travel path, the wheel taper and live axle cause the wheel assembly to be self-centering.

For operations where very short radius curves are encountered it is necessary to use dead axles to avoid slippage between the wheel and rail. In this arrangement bearings are placed between the wheel and axle so the wheels can rotate independently at different rates of rotation as the assembly travels on a curve. It is also necessary to use short center to

center distances between axles to reduce wheel flange scuffing on the rail. For long cars, 4-wheel bogies are used to keep the axle-to-axle distance short. The use of dead axles, particularly if flat wheels are used, eliminates the self-centering characteristic of the live axle, allowing the wheel assemblies to drift laterally until contact is made between flange and rail. If bogies with flat wheels and dead axles are used, this problem becomes severe.

Comments regarding live versus dead axles heard during the series of Holmes & Narver, Inc interviews (33) include:

a. Rotating axles with 3 to 5 degree tapered wheels are self-centering on the rail, thus minimizing flange wear. Four-wheel rail trucks with non-rotating axles and flat wheels are guided by the wheel flanges, causing excessive wear. One or the other flange almost always is running against the ball of the rail causing loss of gage which results in derailment.

b. Live axles will produce less flange scuffing resulting in less rolling resistance.

c. Bearings for a dead axle cost about 50 dollars per wheel versus 200 dollars per wheel for live axles.

d. Muck cars have wheel bearings and fixed axles, therefore, are not self-centering even if the wheels are tapered. The tunneling industry should take advantage of the experience of the railroads.

e. The question of live axles versus dead axles is a very controversial one. It is a very big field to study. The type of axle will not make much difference in rolling resistance since most of the rolling resistance is due to the work done to flatten the wheel tread under heavy loads.

f. Live axles do tend to center the cars as they move but tunnel rail systems are not built with the accuracy of mainline railroads, so the improvement from live axles would be very small.

g. The use of 4-wheel dollies with dead axles rather than two axles on muck cars cause lots of problems.

h. The cars are 26 to 28 feet long and have short trucks. The truck tends to turn and hit one rail, then the other.

i. We are considering use of live axles on our next tunnel job.

j. The muck cars, with 24-inch wheels and live axles, show no flange wear.

k. Flange wear is usally caused by tight gage or not opening the gage on curves.

Locomotives and Cars

Several problem areas related to locomotives and muck cars were identified during the Holmes & Narver interviews (33) and the 1977 Keystone Workshop* (91). Typical comments include:

a. Prohibition of diesel power would greatly increase the cost of tunneling. It would make the cost of underground mining prohibitively expensive and would greatly increase the frequency and severity of accidents.

b. There are no technical problems which limit rail haulage up to 800 tph on grades up to 5 percent, provided diesel locomotives are used.

c. The diesel locomotive provides a safe and reliable form of power in underground operations. The price is generally lower than an electric unit.

d. The cost of the electrification system for electric powered locomotives is high, ranging from 80,000 to more than 100,000 dollars per track mile. In mining operations this high initial cost can be offset by savings in locomotive maintenance and operation costs.

e. Larger trains are needed to decrease the manpower requirement and allow better scheduling of the material flow. The size of the train is controlled by the locomotive. An 8-wheel locomotive of small cross section is needed. The wheelbase on current 4-wheel locomotives is so short that they oscillate up and down longitudinally, tearing up the ends of the rail cars and putting excess loads on single axles.

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* The Keystone Workshop was conducted August 3-5, 1977, at Keystone, Colorado under the sponsorship of the U.S. Department of Transportation, Urban Mass Transportation Administration, Office of Technology Development and Deployment, and Office of Rail Technology. The workshop brought together for several days invited experts on various materials handling systems for underground use. Three keynote speakers evaluated the state of the art of materials handling systems in underground construction, metal mining and nonmetal (coal) mining. Seven more experts in particular materials handling systems also presented formal papers. The workshop participants were then divided into seven working groups (one for each type of material handling system) to discuss the state of the art, to identify areas requiring additional research and development, and to define priorities. A written summary of this thinking was formalized by each group for presentation at the final conference meeting. The workshop sessions were guided by a questionnaire which was distributed to all participants prior to the workshop to stimulate advance consideration of the questions.

f. An 8-wheel locomotive is needed to take curves better. It should be diesel-electric as they are cleaner and have better operating characteristics.

g. The basic design of the diesel locomotive was done about 1932 and not much change has been made. It needs modernization.

h. Larger diameter wheels should be used for higher speed muck cars.

i. There have been lots of problems with slippage when using a rail system on a 2.5 percent grade.

j. Loaded muck cars have been hauled up a 6 percent grade with a 15T locomotive. There are many 5 percent grades in English coal mines.

k. The maximum grade for a rail system is 10 percent, even for a gravity assisted transit system.

l. In England a dual drive locomotive system has been developed which can travel at 10 mph with the conventional diesel drive and 3 to 5 mph on a 25 percent grade when using a hydraulic rack and pinion drive.

m. Runaways cannot be controlled on grades steeper than 4 percent. Brakes on muck cars are not successful.

n. Longer trains of smaller cross section are needed. The major thing needed in rail haulage is better locomotives. Schedule 24 which sets ventilation requirements is completely obsolete.

o. OSHA frowns on trolley wire systems in tunnel construction since people may be working 1000 feet back of the heading. This leaves diesel, battery or diesel-electric as possibilities, and battery is too slow.

p. Dumping muck from cars is often a problem. Self-cleaning muck cars are needed.

<u>Loading</u>

Three systems are commonly used to receive muck from the mole and place it in rail cars. They all have three features in common: a conveyor to carry the muck from the mole to the car, no muck storage capacity, and they are pulled ahead by the mole. They are generally advanced concurrently with the boring stroke. Double track systems are used in tunnels larger than 15 feet diameter (inside the supports).

A gantry conveyor with single track is used in tunnels less than 15 feet in diameter, in short tunnels, on tunnels with very sharp radius (less than 250') curves, and where very low penetration rates are anticipated. This system consists of a frame supporting a conveyor under which the muck train rides on rails. The frame is either a full box or a box open at the bottom (inverted U). The full box has wheels which ride on the mainline rail; the

open box has skids which slide outside the mainline rail on the moled invert or wheels which ride on rails outside the mainline rail. The mainline rail must be laid between the mole and the conveyor (the bulk of the mole prohibits laying the rail under the mole) requiring a long, trussed conveyor span, ahead of the gantry section under which the rail is laid. The full box section requires climber points from the mainline rail to the gantry rail. Derailments often occur here. Minimum storage for materials is available. Trains of muck cars are loaded while being moved under the conveyor end discharge by a locomotive or a car mover. A California switch is either pulled along with the conveyor or is parked within 1000 feet of the end of the conveyor and advanced weekly. When the train is full, the mole must stop boring while the locomotive removes the train from under the conveyor, pulls it onto the California switch, runs around the turnout, and pushes an empty train back under the conveyor. The mole is regripped during this shutdown. To prevent muck spillage between cars, a piece of plywood is laid between the car ends and the muck flipped by a laborer into the car after it passes the conveyor discharge. Advantages of this system compared to double track floors are low first cost, faster erection, and lower maintenance. Disadvantages are delay to change trains and minimum storage for tools and materials.

Both double track systems utilize a wide floor, centered and riding on the mainline rail, supporting two parallel tracks, commonly allowing 6 inches of passing clearance between trains. Haulage equipment rides up climber points from the mainline rail to the tracks on the floor. A turnout directs the equipment to the chosen side. The floors commonly use concrete or steel ballast to prevent tipping when a loaded train is on one side with no train on the other. The front 30 feet of the floor is normally reserved for supply car parking and storage. Rail is laid under the mole in 20-foot diameter and larger tunnels. When rail must be laid behind the mole, a separate conveyor is used to span the rail laying area. The mole does not have to shut down for an empty train to be switched into loading position. A California switch is placed halfway between the end of the floor and the dump when the tunnel is so long as to require two trains on the haul, but is never trailed behind the floor.

Double track floors cost $275,000 to $325,000 depending on the length. With the conveyor mounted along the center of a double track system, muck is discharged from the conveyor to either side with a traveling plow or tripper. The train is stationary while being loaded; thus, a locomotive is not required to index the train under the conveyor discharge. The next empty train is placed on the empty side of the floor; the plow angle is reversed or the tripper's crossbelt direction is reversed, discharging muck to the new train. The locomotive runs around the turnout to remove the loaded train. Locomotive width is restricted only by passing track clearance (at the dump, shaft, or yard) and by conveyor support clearance on the floor, as the locomotive does not have to run alongside the train on the floor. Muck cars are always parked in identical position for loading; spillage between cars is prevented by "muck gables," rooflike structures that deflect the muck, falling from the conveyor, into the cars. A plow will fit in a 15-foot tunnel, whereas 19 feet is the minimum tunnel with enough headroom for a tripper.

The other form of double track system makes use of a car shifter floor. Muck is discharged off the end of a skewed conveyor into cars moved with a system of chains. The conveyor skews from centerline of the floor at the mole conveyor to be centered over the muck car at the discharge end. Empty cars are placed on one side of the floor by the locomotive where they are engaged by the "car-in" chain. This chain pulls the empty train toward the heading end of the floor where the muck cars are uncoupled and placed on a "car shifter" which traverses them laterally across the floor to a position in line with the other track. The car is then engaged by the "car-out" chain, which pulls it off the shifter, couples it to the car being loaded, and pulls it under the conveyor discharge. The shifter returns to the empty side to get another car. The locomotive runs around the turnout and removes loaded cars after they are uncoupled from the car being loaded. The operator on the floor runs the conveyor, car shifter, car mover chains and a flop gate that prevents spillage between the cars. The locomotive must pass the loaded train on the floor when placing empty cars at the "car-in" chain. Thus locomotive width is limited to 6 or 8 inches wider than the muck cars.

Advantages and disadvantages of the shifter floor as compared to the tripper floor are:

Advantages:

a. larger storage deck

b. better dust control at conveyor discharge

c. no plow or tripper to maintain

d. less conveyor belt wear

e. faster erection due to less superstructure

f. will traverse sharper curves

Disadvantages:

a. car-moving equipment to maintain

b. 40 to 60 feet longer overall length

c. restricted locomotive width

Unloading

Muck cars are unloaded by any one of several methods depending upon the design of the car.

The most frequently used method for shallow urban tunnels is the lift-off box. In this method, the muck boxes rest freely on the wheeled base of the muck car. The locomotive moves the train into position where a muck box is lifted by crane or hoist from the base to the surface where the muck is dumped onto a muck pile or into a hopper by overturning the muck box. The

muck box is returned to the base and the train moved ahead to position the next car.

If crane lift is used, the box is usually lifted from the base by attaching a lifting frame, or stiff back, to trunnions at the ends of the box which is lifted freely or along guides to prevent the box from turning. If hoist lift is used, the box is usually lifted along guides with a scroll at the top to tip the box. A skip cartridge has been used to engage the muck box by attaching to a heavy frame around the top edge of the box. This device makes it possible to engage, lift, and dump muck boxes automatically as the train is advanced through the skip cartridge. No bottom man is needed to attach the muck box to the hoist. This cost saving is offset to some degree by the increased cost of the equipment and its installation.

Other methods of unloading are rotary dump and side or bottom dump cars. Rotary dump systems use rotary couplers between cars which permit a car to be rotated 180 or 360 degrees while still coupled in the train. This provides rapid dumping of an entire train. Side dump or bottom dump cars provide even faster unloading as the train continues to move slowly throughout the unloading cycle. Scrolls are used to guide the falling away and closure of the car bottom or tipping of the car body as the train moves through the unloading station. Alternatively, hydraulic or pneumatic pistons are used to control the dumping action of side dumping cars.

HOISTING

Hoisting is accomplished by cranes or hoists which are similar in principle of operation. Both lift intermittently by attaching a line (wire rope) to the load and retracting the line by winding it on a rotating drum. The capacity (tph) of a crane or hoist is determined by the size of the payload, the velocity at which the load is lifted, and the height of the lift. Reducing the speed for a given payload reduces the horsepower required but it also reduces the capacity, unless a larger payload is used. A larger payload increases the rope diameter which, in turn, increases the drum diameter and the size of other mechanical components. For a given depth and capacity, there is an optimum (minimum cost) load. Increasing the depth increases the cycle time and decreases the capacity unless a larger load or a higher velocity is used. At the shallow depths found in tunnel construction, the maximum practical speed is limited to relatively low values, at the point where the lift consists of only acceleration and deceleration with no full speed time.

The designs for cranes or hoists have not been optimized for the complex interrelationship of payload, speed, horsepower, depth, capacity, and cost in the range of interest for tunnel construction. In general, hoists have been developed for lifting from deep underground mining operations and cranes have been developed as construction machines where lift height requirements are relatively low.

There is considerable agreement among contractors (33) that shaft hoisting capacity limits, or may soon limit, the advance rate of tunnels

driven from a shaft. Equipment manufacturers, however, feel that cranes and hoists have the capability to handle the projected requirements at competitive cost if the equipment is designed for the specific requirements as part of an integrated material handling system.

The panel reviewing hoisting at the Keystone Workshop (26) concluded that the equipment and application technology presently available are adequate for present day mining and construction shaft hoisting. However, the panel noted a problem of distribution of this knowledge especially in the area of shallow shaft hoisting and suggested that a survey be conducted of the state of the art of the problems of design, selection and application of materials handling systems in shallow shafts (less than 500 feet).

The features which distinguish between a crane and a hoist are the boom of the crane and the headframe of the hoist. The crane boom may be fixed or rotatable, and the crane may be fixed in place, movable or mobile. The drum in a hoist may be at the top of the headframe or in a hoist house at ground level. The drum of a crane is always located at the base of the boom. Hoists are either drum hoists that have one end of the rope or ropes anchored to the drum and use the drum for rope storage, or are friction hoists that use friction between the rope and rotating drum to drive the rope. Cranes are always drum type. Friction hoists or balanced skips use either a deadweight to balance the load, or payload can be handled alternately on both ends of the rope with the empty skip or box partially balancing the payload.

<u>Cranes</u>

Comments heard during interviews with industry (33) and at the Keystone Workshop (91) regarding the use of cranes for hoisting through a shaft include:

a. Lifting muck by cranes is not satisfactory.

b. A crane cannot hoist 850 tph up a 250-foot deep shaft. Cranes are marginal to hoist from deeper than 100 feet.

c. There are no cranes on the market to hoist from 200 feet.

d. As depth increases, the box lift method using a crane becomes inefficient at about 70 feet.

e. Where allowed by regulations, cranes can be used to 200 feet deep if the muck quantity is not too great. The critical depth is determined by the amount of material to be handled.

f. A crane is preferred for muck lifting because it can be used for shaft sinking, for lowering equipment during installation and for lifting muck boxes and lowering ribs and supplies during tunnel construction.

g. For relatively shallow shafts, say less than 125 feet, a crane hoisting system is standard.

h. Maintenance and parts should cost less than one percent per year of capital cost based on operation 83 percent of time (50-minute hours).

i. Cycle time for crane lifting of muck boxes is typically about 3.5 minutes for lifts of less than 70 feet.

j. Most of the longer cycle time of the crane is due to time required for hooking and unhooking cars and replacing cars on the bogies or on the rail.

Several suggestions were made (33) for modification of cranes to be used for muck lifting.

a. Buy cranes for stationary operation with pedestal mounts to save the cost of the crawlers. Crawlers can be added later if the crane is to be used for other type work.

b. Use one part line and a longer drum if the lift is over 50 feet.

c. Dump onto a muck pile. Dumping into a bin delays the cycle too much.

d. Use electric drive rather than diesel. The initial cost is less, and there is an operating cost saving of one dollar per hour at 300 horsepower. Diesel power can be installed later if needed.

e. Use a larger sheave for low lifts to compensate for the constant flexing of the rope over the sheave.

f. Use wide flange "I" beams as guides to prevent the muck box from turning as it is lifted through the shaft.

g. Increase line speed from the typical 150-160 fpm to 250-300 fpm. This would require changes in horsepower, torque conversion equipment, lagging and rope.

h. Use multiple single part line rather than multi-part line to increase payload.

Scaravilli (74) summarized the advantages of cranes compared to hoists for muck lifting as follows:

a. Lower initial investment.

b. Better portability. This is a large factor especially in segmented jobs, or jobs in which the mucking spread can be advanced to successive shafts.

c. Larger resale market, which increases salvage value.

d. Easier replacement in case of major breakdown.

e. Provides additional service in the yard area (not possible with a hoist).

The disadvantages are:

a. More labor (oiler) required for union job.

b. More experienced operator required.

c. More maintenance.

At least one manufacturer of cranes (14) is directing its attention to the application of the full capability of crane technology for muck lifting. It recognizes the tunnel industry as a unique market and designs for the specific requirements of this market based on investigation of the application of cranes to tunneling. This manufacturer feels that the projected far term requirements for muck lifting can be met by present crane technology which has advanced significantly in recent years. For example, ten years ago a 35 cubic yard dragline bucket was considered large; now 220 cubic yard buckets are used. This manufacturer developed a crane system design using multiple single part lines and a 25 cubic yard skip to handle 465 tph from a depth of 280 feet with a line speed of 300 fpm.

Hoists

Hoists have been in use since the earliest days of mining and construction activity. Although hoist design and technology are based on concepts developed more than one hundred years ago, the payload has increased during the last 30 years, about ten fold. Today, skips of 20- to 30-ton capacity (15 to 20 cubic yards) are operating at speeds over 3000 feet per minute (37). Drum hoists are used to depths over 5000 feet. A 20 cubic yard muck box with section dimensions practical for use in an urban tunnel would be from 18 to 30 feet long.

Despite projections of a substantial number of new shafts required over the next ten-year period, there is only one major manufacturer of hoisting systems in the United States (37). Scaravilli (74), in summarizing the use of hoists for muck removal through a shaft, pointed out some of the advantages and disadvantages compared to cranes. For shafts deeper than about 125 feet, a hoist system is required to gain the advantage of its higher speed and faster dumping. The initial investment is greater for a hoist and the time and cost for installation and removal are greater, but a relatively trouble free operation can be anticipated. Hoists can operate with a skip or a car handling cartridge. If a skip is used it is usually loaded through a holding bin or measuring pocket. This requires substantial overexcavation beneath the invert of the shaft. The bin is filled from either a rotary car dump or self-dumping cars. If the bin is large enough, the hoisting of muck will be nearly independent of the horizontal haulage. If the job is not large enough to justify the cost of a skip loading system, a car handling cartridge can be used. This cartridge will automatically engage and lift a muck box off the car chassis or lift the entire car to the dump scroll at the top. After dumping the car or box is returned to the rails at the invert. The skip method is faster but costs more than the handling cartridge.

Comments heard during interviews with industry (33) regarding the use of hoists for lifting through shafts for tunnel construction include:

a. If a skip hoist system is used, it must be installed before tunnel excavation can begin. This usually takes a month or more. A crane is available immediately to start the tunneling job.

b. A skip pocket requires shutdown every few days to clean up the pocket due to spillage which always occurs. It also needs to be backfilled with concrete at completion of the job. These are added costs to the job.

c. When comparing hoists and cranes on equipment and installation costs, the hoist will lose every time for shallow depths. It is costly to get rid of a mine hoist at the end of a job. The hoist will win on operating and maintenance costs, and on reliability and equipment life.

d. The present system of muck box lifting requires everything to be too exact. A high speed skip is the only answer for depths from 150 to 200 feet. Surge storage and a means of fast skip loading are required.

e. Typically, hoisting equipment used by tunnel contractors was designed for another use. It is not properly applied or used. It is often undersized.

f. Hoists can be used either vertically or on an incline for shallow depths. Nine hundred tons per hour from depths of 200 feet can be handled easily.

g. If balanced skips, winding and unwinding from a single drum, and an automatic hoist are used, 72 cycles per hour could be obtained at a 200-foot depth. About 13 tons per load would be required for 900 tph. The skip would weigh 10 to 12 tons so the total load would be about 25 tons plus the weight of the wire rope. The rope diameter required would be about 2 inches. With a 60:1 ratio of drum to rope diameter, the drum would be about 10 feet in diameter.

h. Hoisting requires a major installation with high cost. It is not easy to put in on a temporary basis since a loading pocket and a head frame are required.

i. For shallow shafts, heavier loads can be carried at slower speeds. For a 200-foot depth requiring 300 feet of lift (60 feet above surface and 40 feet below invert), the maximum speed would probably be 600 feet per minute (10 ft/sec). The cycle would probably be:

	Sec	Ft
Acceleration (@ 2 ft/sec/sec)	5	25
Deceleration	5	25
Slow travel and dump	6	10
Full speed travel (10 ft/sec)	24	240
Loading	10	
	50	300

j. Using a skip hoist with a muck box lifting cartridge and a lift height of 120 feet, the cycle time is 180 seconds average per car. Each car holds 10 cubic yards, giving a capacity of about 270 tph.

k. A shallow depth requires a greater rope factor of safety (up to 8) due to the more frequent flexing of rope around the drum.

l. Delivery times for hoists in the 600 horsepower range are 8 to 14 months depending on the amount of engineering time required and the availability of gears.

m. A rule of thumb is that maximum rope speed (ft/min) is equal to the depth (ft). (In present practice, this speed is often exceeded.)

n. A hydraulic drive hoist is available for a maximum payload of 12 tons using a single line, a 6-foot diameter drum and 450 fpm line speed. The cost is about $125,000 with full automation and controls at top and bottom of the shaft.

o. A properly designed mine hoist has an 85-95 percent availability.

RUBBER TIRE HAULAGE

The use of rubber tire vehicles in tunneling is widespread because the characteristics of many tunnel projects favor their use. Rubber tire vehicles are favored for low muck rate, large tunnel diameter and short haul distance. The size-capacity relationship of rubber-tire vehicles designed for underground haulage determines the practical limit of these parameters for rubber-tire haulage. This is illustrated by the dimensions, capacity, and vehicle frequency shown in Table 18 for typical underground haulage vehicles and specified muck rates. It is easily observed that for the muck rates of interest in a 20-foot diameter tunnel and a typical maximum speed of 12 mph (about 1000 feet per minute), the reach must be relatively short or vehicles must pass in the tunnel. Ten-ton capacity vehicles are about the largest that can pass in a 20-foot tunnel unless passing niches are provided. For the maximum projected muck rates, the vehicle trip rate becomes excessive even for the largest vehicles. Therefore, the use of rubber-tire vehicles for muck haulage in tunneling is restricted to

drill-and-shoot operations which produce muck intermittently at relatively low rates (less than 100 tph). Almost every rock tunnel starts with a drill-and-shoot operation to excavate the development area. This operation is usually supported by a load-haul-dump (LHD) unit for mucking.

TABLE 18. RUBBER-TIRE VEHICLE HAULAGE

Vehicle	Dimensions (Inches)		Capacity (Tons)	Muck Rate (tph)	Vehicle Trips per Hour
	Height	Width			
Telescopic Dump Truck	84	121	20	100 400 900	5 20 45
Load-Haul-Dump	78	84	7.5	100 400 900	13 53 83
Load-Haul-Dump	97	120	20	100 400 900	5 20 45
Rear-Dump Truck	81	84	10	100 400 900	10 40 90
Rear-Dump Truck	82	120	25	100 400 900	4 16 36
Rear-Dump Truck	96	136	40	100 400 900	2.5 10 23

Keating (40) reviewed the use of rubber-tire vehicles for muck haulage in drill-and-shoot tunneling operations. His basic premise is that whatever gets the muck out the fastest should be used; put in the equipment that provides the shortest possible muckout time in the heading. The introduction of the load-haul-dump family of equipment in the late 1960s is recognized as a major advance in rubber-tire haulage.

One disadvantage of rubber-tire vehicles mentioned by Keating is that as they are used over greater distances, the ventilation requirements for the increased horsepower can become excessive. The use of rehandling drifts at approximately 1000-foot intervals throughout the tunnel length is also required for extended lengths. Rubber-tired vehicles are favored over rail for any grades over 3 percent adverse. Rubber-tired equipment can operate on grades up to 27 percent provided there is a good road surface.

The flexibility and range of materials that can be handled by rubber-tire vehicles is another factor in their favor when other conditions are

suitable for their use. For example, if muck were removed from the tunnel by a continuous method (conveyor or pipeline), a rubber-tire vehicle might be practical for haulage of incoming materials.

The mining industry has an increasing number of articulated haul vehicles for underground transport of mined materials and for general utility haulage. These vehicles are low profile and obtain capacity by increasing width. This suits the requirements of mining operations but redesign for the requirements of incoming materials in tunneling operations should produce a vehicle better suited to support continuous muck haulage systems. The quantity flow of incoming materials is small compared to muck flow rates; therefore, vehicle traffic for incoming materials only should be acceptable and the cost probably would be less than for a rail system.

The concept of a pallet transport vehicle with unitized loads which would allow loads to be placed quickly on the vehicle, and quickly removed as a unit should achieve better utilization of the expensive basic vehicle and power unit thus reducing the cost per unit of material transported. In this concept, the pallet would also contribute to preplanning load packages for specific task performance and provide a base for special erection or emplacement equipment. The rubber-tire vehicle would become a pallet transport unit and would be free to perform its transport function during the time material was being loaded onto or unloaded from other pallets. The trailing unit behind the mole would become a storage dock equipped with power units for offloading, unloading pallets and onloading to the vehicle.

It is unlikely that transport of incoming materials will become a constraining factor in tunnel construction. However, at the high advance rates projected for the far term case, it might be necessary to operate more than one vehicle to maintain the flow of incoming materials. This could be done by providing passing niches or by providing transfer staging docks along the tunnel. The rapid offloading and onloading capability of the pallet concept should make the transfer staging concept feasible.

The pallet transport vehicle would need to be completely bidirectional. It should run at the same speed (up to 20 mph) and be equally steerable when operating in either direction in the tunnel. Semiautomatic or safety-limited steering might be employed.

Scaravilli (74) summarized the disadvantages of rubber-tire haulage as:

a. Far more diesel horsepower is required than for rail for the same amount of muck, with increased ventilation requirements and fuel cost.

b. Inverts and haulways must be maintained constantly.

c. Great amount of expense due to abuse suffered by tires. (Although significant improvement has been made in tire quality and in the use of beadless tires, this remains a major expense item.)

d. More individual equipment units to maintain and operate.

e. Intermodal transfer of muck is more complex.

f. Increased operating and maintenance personnel and cost.

g. Limited by length of tunnel and speed of units.

The advantages of rubber-tire vehicles are flexibility with low installation cost and high portability from site to site.

One of the major concerns of the panel considering rubber-tire haulage at the Keystone Workshop (26) was that if regulations further restrict the use of diesel power underground, it will put a severe limit on the application of rubber-tire vehicles in tunneling.

Surface haulage of muck is almost entirely by rubber-tire vehicles. The vehicles used are standard bulk haulage trucks with up to ten wheels. Equipment to handle the maximum projected muck rate appears to be available, although it may become necessary to provide either two truck loading stations at the shaft or very large surge bin capacity. Ten-wheel mining trucks with payload capacities up to 235 tons are available, but may not be suitable for road haulage.

CONCLUSIONS

The basic technology of the conventional haulage systems (rail, crane, hoist) used for underground transport appears to be adequate for near term requirements although improvement is needed in design, installation, operation, and maintenance of the systems to obtain full advantage of the basic capabilities. As advance rates increase more attention will need to be given to total system integration and to extension of the horizontal transport system.

Lifting through the shaft will become a constraining factor before the horizontal transport system becomes saturated. Design of a hoisting system for the specific requirements of tunnel construction should be based on the principles common to cranes and hoists rather than modification of designs developed for other applications.

The technology of rubber-tire vehicles for underground haulage appears to be adequate to provide a basis for development of a specialized vehicle for palletized transport of incoming materials in support of continuous methods of muck transport.

6. BELT CONVEYORS FOR HORIZONTAL TRANSPORT

STATE OF DEVELOPMENT

Belt conveyors have been used for horizontal transport of bulk materials for many years. Over the years, advances in available materials and design methods have resulted in the evolution of new concepts and improved components which have provided for increased capacities, increased flight lengths, longer equipment life, less downtime, and the ability to accommodate special requirements. Belt conveyors are now in service for overland transport which far exceed the foreseeable capacity and flight requirements for tunnel construction. For example, belt conveyors with capacities up to 30,000 tph are in wide use throughout the world handling many types of bulk materials (49). These conveyors, with belt widths up to 120 inches, operate at belt speeds up to 1200 feet per minute. One phosphate handling system in Africa has a single flight length of 12 miles and covers a distance of 62 miles with ten sections.

A system called the "belt-car" conveyor has been developed in the USSR especially to handle large lump sizes (57). This system can accommodate maximum lump sizes up to 60 inches (conventional belt conveyors are limited to maximum lump size of approximately 12 inches) and is reported to be using conveyor belts nearly 12 feet wide to obtain capacities up to 40,000 tph. The belt-car conveyor consists of a conventional flat belt supported at intervals of 5 to 7 feet by traveling "cars" consisting of a troughed cross strap between rollers, on which the cars move along rails. The cars are connected by two endless chains to maintain their spacing. The conveyor belt, driven by conventional drive pulleys, drives the cars along the rails by the friction force between the belt and the troughed cross straps which support the belt.

As the belt and car approach the drive pulley, the belt separates from the car and passes over the pulley. The car, attached to the chain, passes over a sprocket and makes the return flight in the inverted position. A short distance out from the loading point, in front of the tail pulley, the cars pass around another sprocket which uprights them for receiving the loaded belt. Although this concept is of interest for drill-and-shoot mining operations because of its high capacity and large permissible lump size, it appears to offer no advantage over other concepts for transport of muck produced by a tunnel boring machine (TBM).

The principal application of belt conveyors for underground haulage is in coal mines where belts are used extensively for intermediate transportation from the face haulage discharge point to the main haulage system and to a lesser extent for mainline transportation (88). In general for coal haulage, belts are considered to be reliable, high capacity systems with high capital cost and low operating costs. Belts used in coal mines are usually from 36 inches to 48 inches wide.

The major concerns which deter contractors in the use of belt conveyors for muck transport are high initial cost, work stoppage in the event of failure at any point of the conveyor system, the need for another system for

the haulage of inbound materials, and the difficulty of negotiating curves and extending the conveyor in pace with the mole. Typical comments heard during a series of interviews conducted by Holmes & Narver, Inc. (33) and at the Keystone Workshop (91) are:

a. Conveyors all the way from the heading to the shaft are not economical.

b. Muck removal using conveyor alone from the heading to the shaft or portal is, generally speaking, not practical. Although the mines, which spread out in several directions, use conveyor haulage to great advantage, it is not adaptable to tunnels which are linear and are continually moving away from the belt loading point.

c. If conveyor is used, you have to devise a separate method of bringing ribs, lagging, tools and repair parts into the heading.

d. A combination conveyor and rail system would be too expensive. The rail system alone can keep up with the tunnel advance rate.

e. I don't know of any case where only a conveyor was used for muck haulage. Usually a conveyor is used for the first few hundred feet (about 300) and rail haulage is used for the remaining distance.

f. Conveyors might be used for long distances or where side drifts come in.

g. Conveyors might be used all the way if relatively short haul, particularly if the contractor has several contracts so he could make multiple use of the conveyor system.

h. Some attempts to use conveyors in tunnels have not been designed properly. For example, one job had trouble with water getting in motors and belt sag due to excessive idler spacing.

i. Higher speeds should be considered for conveyors to reduce belt width, reduce roller width and cost, and reduce structural support requirements.

j. A conveyor system can be designed to do the job specified and meet a guarantee, if one is willing to pay the price.

k. If oversize pieces give problems when mucking with a conveyor, they can be thrown aside and broken up or mucked out later by train or truck.

l. A conveyor all the way out the tunnel would require water sprays to prevent dust. Dust from a conveyor is a problem.

m. A plow is better than a tripper for unloading the belt.

n. Transverse travel on a tripper is not desirable. As much sophistication and complexity as possible should be eliminated from the entire system.

o. Transfer points in conveyor system cause problems, particularly when there is wet sticky material.

p. The belt conveyor should be 99.9 percent available. One dam job had only 4 hours downtime in 3 years due to the conveyor system. Coal mines experience about 1.5% downtime due to conveyors.

q. When used in tunnel construction, the average segment of conveyor is installed only about 55 percent of the time. The last segment installed is used only about 5 percent of the time.

r. For a conveyor system, the power (drive) needs to be increased as the belt is extended. If the ultimate power is installed initially, it is only 50 percent used, on the average.

s. Bad features of conveyors are poor reliability and lack of surge storage. One shift of surge storage should be provided.

t. If a conveyor system were used for muck, you could probably get by with rubber tired vehicles for other haulage requirements, if a ballasted invert were used.

SYSTEM DEVELOPMENTS

The belt conveyor system used in bulk material transport consists of the following elements:

a. Belt - The material carrying medium; normally a cord or mat reinforcing structure of steel or synthetic fibers covered with natural or synthetic elastomer materials.

b. Idler Rollers - Rollers which support the loaded flight of the belt and which form or "train" the belt into a trough.

c. Return Rollers - Rollers (not troughed) which support and guide the return flight of the belt.

d. Supports - Individual stands, hangers or brackets stabilized by wire rope to support the roller assemblies from the floor, ceiling or sidewall. Also, a rigid structure or frame to bridge between points.

e. Tail Pulley - The pulley at the end of the segment where material is added. The pulley absorbs the tension and turns the belt 180 degrees.

f. Head Pulley - The pulley near the end of the segment where material is delivered or removed from the belt. In simple configurations, this can be the drive pulley.

g. Drive Assembly - The point at which power is added to the conveyor system. A powered drum driven by a motor and transmission, with idler pulleys to attain the proper wrap for power transmission.

h. Tensioning Device - An auxiliary mechanism to keep a relatively constant tension on the belt, and absorb starting and operating load fluctuations. Types include gravity and hydraulic force governing devices.

i. Accessories - Attachments added to perform specific functions such as belt cleaning, impact absorption at the loading point, belt tracking control, belt tear sensing, or belt unloading.

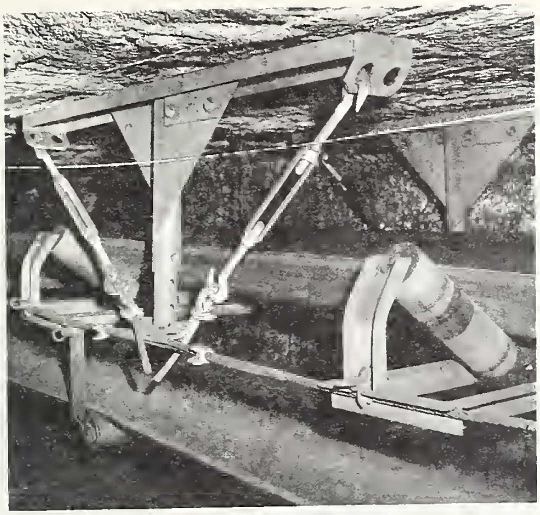
Belting

The most important and expensive element of a belt conveyor is the belting which can reach 40 percent of the cost of the total installation (87). In recent years significant advances have been made in belt engineering and fabrication to provide greater tensile strengths, less stretch, improved impact resistance, greater toughness and flexibility, elimination of tearing and ply separation, easier field splicing, less maintenance, and overall cost reduction. These improvements in design include solid woven, plyless belt carcasses, straight wrap construction in which the tension cords are straight rather than crimped as in older belt designs, the use of steel cord belting, and the elimination of capped edges. The use of synthetic materials such as nylon, polyester, polyvinyl chloride and neoprene has also contributed significantly to superior belting. The improved belting available permits increases in conveyor flight lengths, higher tensions with smaller tensioning (takeup) devices, and smaller pulley diameters. Also the reduced belt thickness allows smaller reels to be used for shipping and belt extension.

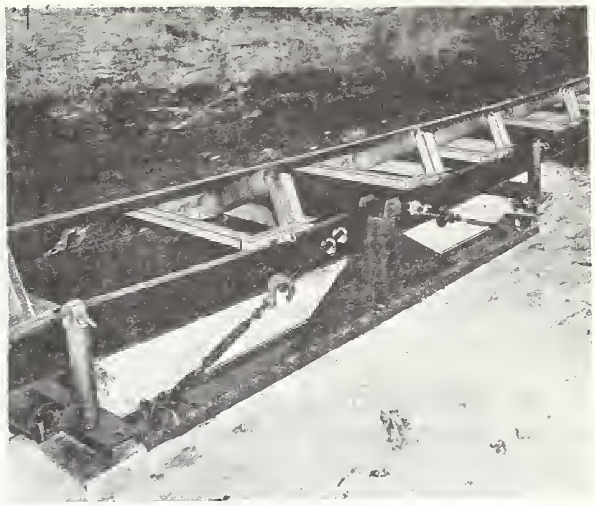
In addition to the improvements that have been made in flat belts, a variety of special molded belts have been developed as solutions to particular problems. These include fluted or convoluted designs to provide flexibility for negotiating curves, fluted side walls for increased capacity, and molded grooves along both sides of the belt to engage the supporting wire rope in one special design.

Supports and Idlers

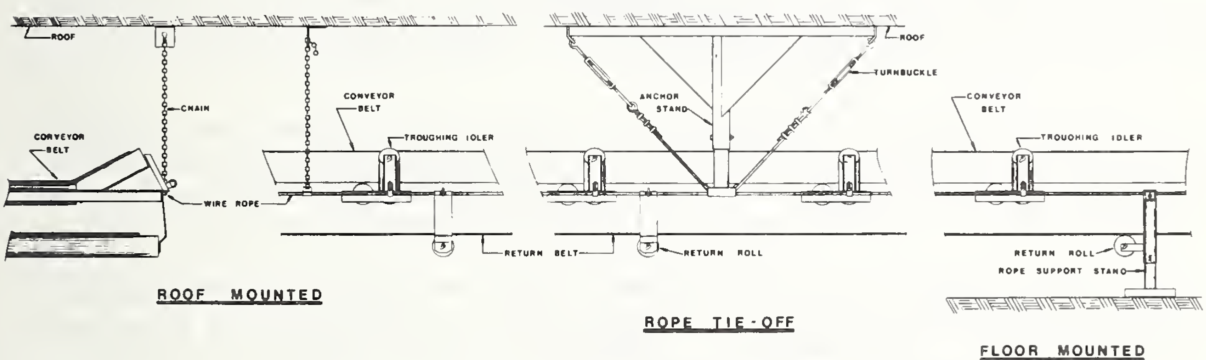
The supporting structure generally used for belt conveyors in coal mines is the wire rope frame either floor mounted or suspended from the roof (88) as shown in Figure 9. This system provides adequate support for the loaded belt with minimum materials used in the supporting structure resulting in lower cost.



ROOF HUNG CONVEYOR



FLOOR MOUNTED CONVEYOR



Courtesy of Continental Conveyor & Equipment Company.

FIGURE 9. WIRE ROPE SUPPORTED CONVEYOR

In this design conventional idler assemblies are supported at 5- to 10-foot intervals by wire rope stretched between distant anchor points with intermediate rope support stands or chains as needed. These supports are easily adjusted for height and alignment.

The flexibility provided by the independent roller assemblies facilitates easier extension of the conveyor and easier belt alignment. With roof suspension, cleaning under the belt is easier. The use of wire rope conveyors has also gained wide acceptance in overland belt applications due to reduced costs for supporting steelwork, site preparation and installation.

By adapting the support stands and anchors to fit a round surface, the system should work well in a tunnel. Overhead suspension could also be used, but might be considered unsafe unless some form of shielding were provided to protect against rock falling from the belt. This would add significantly to the cost of installation.

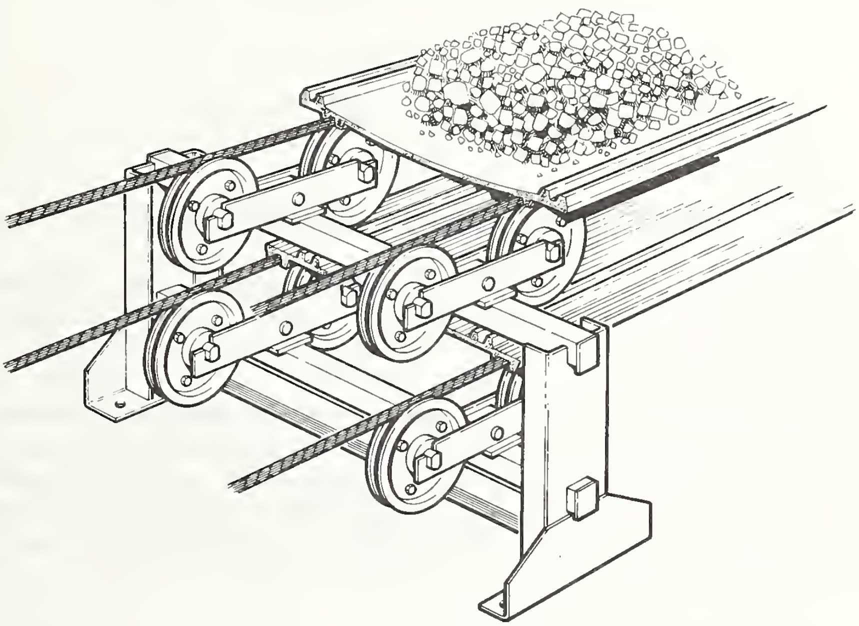
Another concept which has been commercially applied for the mining and bulk materials handling industry throughout the world for more than 20 years is the Cable Belt (6, 82) shown in Figure 10. In this concept the carrying and drive functions are separated. The carrying medium (the belt) sustains no drive tension and is designed with transverse stiffeners to carry the material being conveyed. As it is not attached to the supporting cables, it acts as a simple beam and forms a natural trough under the material load, thus eliminating the need for troughing idlers (the second most costly element of a conventional belt conveyor).

The tension cables, up to 2 inches in diameter, are driven from a single drive unit (up to 4000 hp); or intermediate drive units which are smaller and more compact may be used for underground applications. The drive cables are supported on line pulleys spaced at 10-foot to 50-foot intervals.

This concept was originally developed to achieve greater flight lengths than were then possible with the available belts. Flights up to 9 miles are in operation. Later developments in components of the concept provide for practical shorter lengths, easier extensibility and the use of multiple drives.

With the introduction of thinner, more flexible belts of greater strength, it has been possible to use idlers with a greater troughing angle to obtain more capacity for a given belt width. A capacity increase of slightly more than 25 percent can be achieved with a change from 20-degree to 35-degree idlers (88). Another development which has contributed to improved reliability and reduced system cost is low resistance, greased-for-life idlers with improved end seals to keep out dirt and moisture.

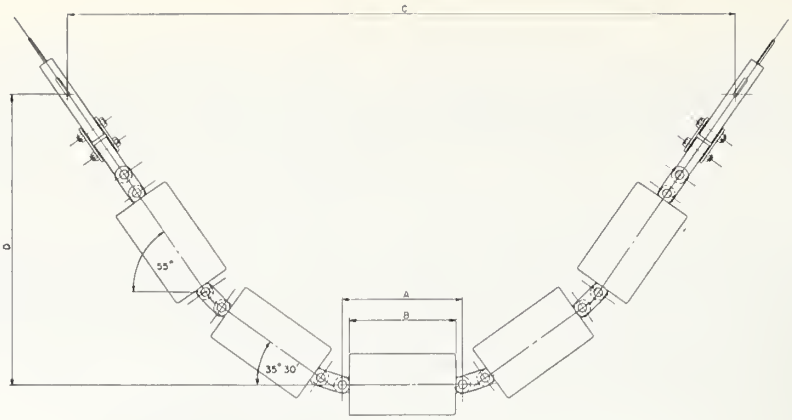
Development in Europe of the garland idler (Figure 11), a 3- or 5-roll idler pivoted between the rolls, has introduced better training and belt control than obtainable with rigid frame idlers. Because of its ability to



Typical CABLE BELT Line stand showing
Polyrims and Rocker Bar Arrangement

Courtesy of Cable Belt Limited

FIGURE 10. CABLE BELT CONVEYOR



Courtesy of Stephens-Adamson Canada

FIGURE 11. GARLAND IMPACT IDLER

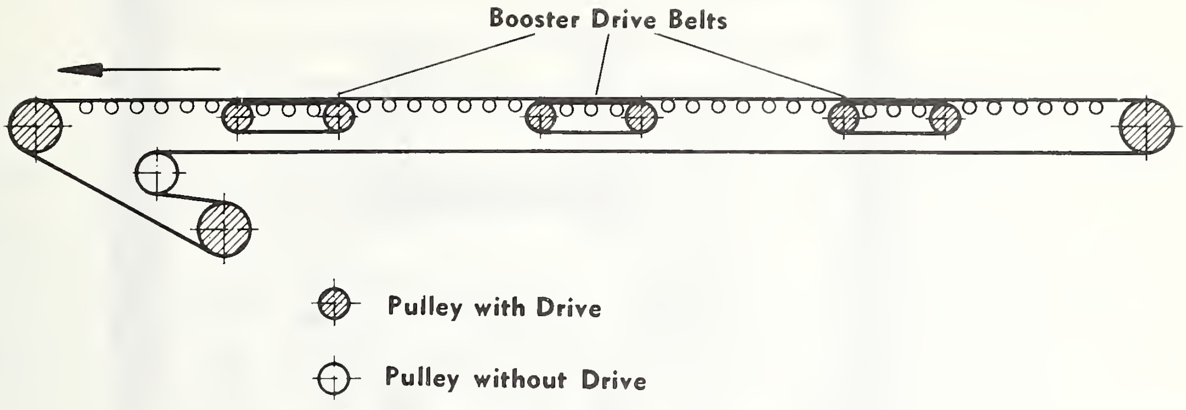
change its profile, this idler has made it possible for flat belts to negotiate long radius, horizontal curves. Work is underway to shorten the radius of curvature.

Efforts to increase idler spacing to reduce cost have been successful only to a limited degree as the capacity of the individual idlers and supports must be increased when a smaller number of units is used. Also idler spacing greater than about 5 feet tends to increase the artificial friction coefficient (49) which increases the belt width and power required.

Drives

As the requirement for more power input to the belt increased, several variations of the dual drive were developed (87). This concept makes use of two driving pulleys. In its simplest version, power is applied to the head pulley and to the tail pulley. Other versions employ one or more auxiliary driven pulleys located near the head pulley, and the head pulley may or may not be powered. In theory, as many driving pulleys as needed could be used. However, this approach does not significantly reduce belt tension in the load carrying flight unless an intermediate drive pulley is installed in this flight. If this is done, it creates a load transfer point which is undesirable.

To overcome this problem in long, single flight conveyors, two concepts for intermediate drives have been developed to commercial application. The T-T type (46) shown in Figure 12 uses booster drive belts to supply additional power to the haulage belt. The head pulley, tail pulley and auxiliary pulley can also be powered, as shown. The tractive force of the booster belts is transmitted to the carrier belt only by the friction contact between the belts. The head pulley, or the head and tail pulleys, of the booster belt can be powered. This concept has worked without problems in a system with 16,000 tph capacity and a 3600-foot flight. The pulleys in a booster drive unit are on 250-foot centers to obtain sufficient friction surface between the belts.



Source: Krumrey (46), Skilling's Mining Review, February 19, 1977

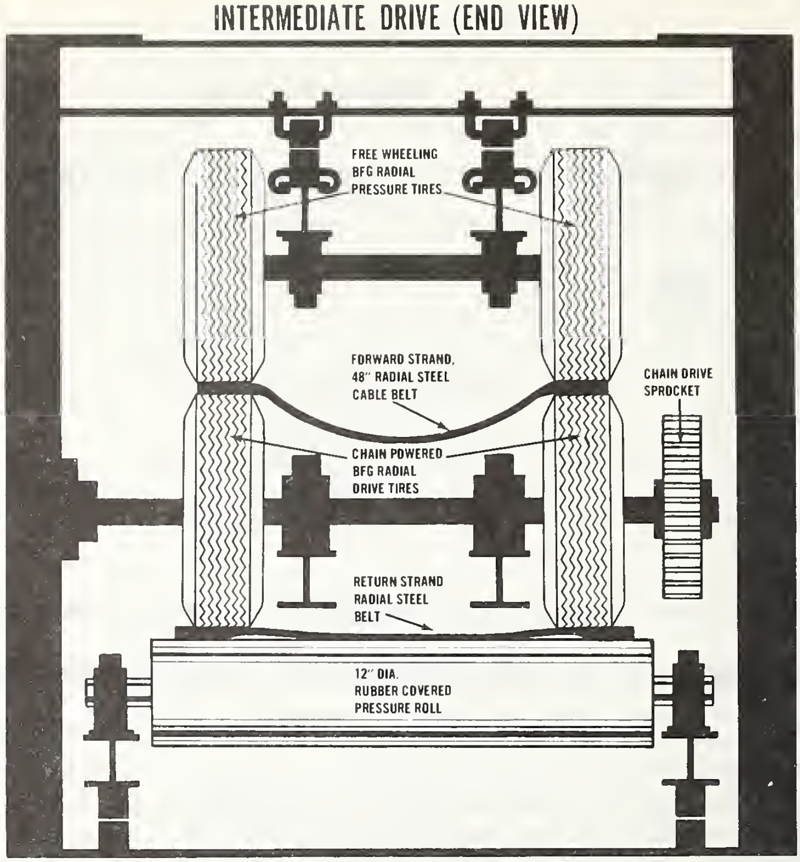
FIGURE 12. T-T TYPE INTERMEDIATE DRIVE FOR BELT CONVEYOR

The other successful intermediate drive system, developed jointly by B. F. Goodrich and Continental Conveyor Company (9, 75) uses steel belted radial tires to apply tractive force to the edges of a BFG Radial Steel belt as shown in Figure 13. The Radial Steel belt is reinforced longitudinally by steel cables embedded in the edges where tension is concentrated. This leaves the center of the belt flexible to "hammock" and conform to the load. At least two intermediate drive conveyor systems are in commercial operation. One has a 2-3/4 mile-long overland flight hauling phosphate (2500 tph) from an open pit mine to a processing plant for American Cyanamid Corporation in Florida; the other is a 7200-foot single flight hauling coal (up to 3000 tph) from a Kaiser Steel underground mine at Raton, New Mexico. The phosphate conveyor simultaneously hauls sand tailings at 1400 tph on the return flight to the open pit. The synchronized 200-hp drives are spaced up to 3000 feet apart, placed where they will be most effective.

Other types of intermediate drives, such as powered rollers and linear induction motor systems, have been proposed, but none has been as successful as the T-T system and pneumatic tire drive.

The use of multiple drives increases the availability of the system as the loss of a drive unit only results in reducing the total power available to the belt. In tunnel driving, maximum power is needed only during periods of peak penetration when the heading is near the end of the reach.

The use of intermediate drives, particularly when a series of units is used, can produce a significant increase in electrical system cost since the drive units must be synchronized for load following and a carefully programmed start-up routine must be used.



Courtesy of Continental Conveyor & Equipment Company

FIGURE 13. INTERMEDIATE DRIVE FOR CONVEYOR SYSTEM

CONCEPTS FOR EXTENSION AND CURVES

Coal Mine Systems

Since the arrival in coal mines of continuous mining machines in the late 1940s, the potential advantages of continuous face haulage have been increasingly apparent. There have been many attempts to design haulage systems to match the continuous miners, but few of them have performed well enough at reasonable cost to survive. Cowan reviewed several of these designs in a 1975 report for the U.S. Bureau of Mines (11) and at the Keystone Workshop on Materials Handling for Tunnel Construction (12).

The capacity, flexibility and mobility requirements for a continuous face haulage system, particularly for room and pillar mining, are severe. For example, some of the requirements are:

a. A capacity to handle 480 to 720 tph average and twice that amount during brief surges.

b. Lump sizes normally up to 12-inch cubes and occasional oversize slabs.

c. Advance and retract capability of 200 to 300 feet which can be extended to 400 to 600 feet in the future.

d. Advance and retract speeds up to 60 or 80 feet per minute on grades of 25 to 30 percent.

e. Negotiate simultaneously 5 to 6 horizontal bends (up to 90 degrees) with 15- to 20-foot radii.

f. Vertical flexibility up to 18 inches in 20 feet of reach.

In all respects, these criteria are more severe than required for a continuous haulage system for tunnel construction. For example, the projected requirements for the far term tunnel haulage system are:

a. Peak capacity of 900 tph, rather than 1400 tph.

b. Maximum lump size about 6 to 8 inches, rather than 12 inches.

c. Maximum advance of 600 fpd (with no retraction) with a maximum extension rate of 6 feet per minute, rather than continuous, repetitious advances and retractions up to 600 feet at rates of 60 to 80 feet per minute.

d. Maximum grades of 10 percent, rather than 25 to 30 percent.

e. Less than four horizontal turns (up to 90 degrees) in two miles with minimum radii of 750 feet, rather than up to 6 bends with radii of less than 20 feet within a few hundred yards.

f. Very little vertical flexibility, rather than 18 inches in 20 feet.

The conveyor concepts reviewed by Cowan (11, 12) include:

a. Bridge conveyors, bridge carrier systems

b. Extensible belt conveyor systems

c. Flexible conveyor belt systems

d. Monorail-mounted transfer conveyor

e. Cascading conveyor systems

   (1) Jeffrey Moleveyor

   (2) Hewitt-Robins Mineveyor

   (3) Joy Push Button Miner Train

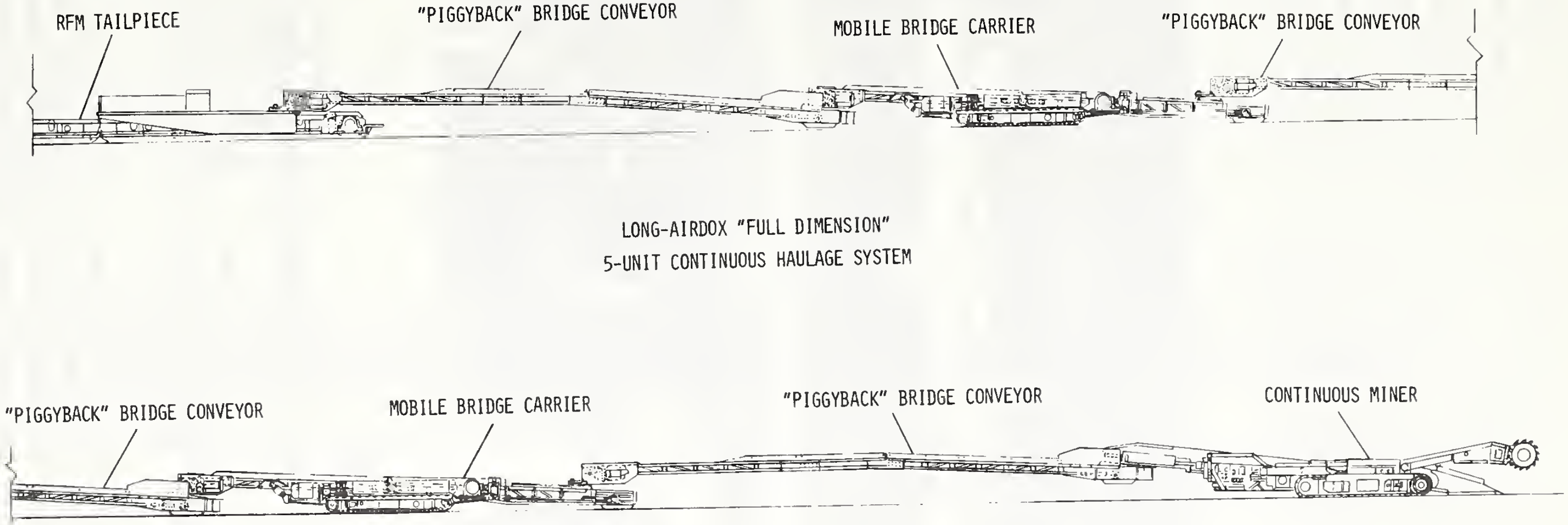
(4) Consolidation Coal Company Banana Wagon

(5) Joy 2PC-Portable Conveyor

The bridge conveyor-bridge carrier system (Figure 14) is a series of alternating bridge conveyors and supporting mobile bridge carriers with either chain-type or belt-type conveyors on the bridges and the carriers. Because the conveyors on each unit are independently driven, there are material transfer points at each pivoting connection between carrier and bridge. Each carrier is independently powered and driven by an operator to maneuver the combination of carriers and bridges behind the continuous miner. To achieve the required flexibility, the length of the bridges and carriers (the distance between pivot points) is kept short. Bridge conveyors vary in length from 30 to 45 feet. Carriers are about 30 feet in length. This system is the most frequently used for continuous face haulage. For tunnel applications, much longer versions of this approach with less costly unmanned carrier units would be required.

The extensible belt conveyor system developed for coal mine application has a crawler mounted drive-storage unit which includes the belt drive, belt storage capacity and belt take-up all in one frame. The belt is extended by pulling the tail section away from the drive-storage unit as the miner moves away from the panel belt. Intermediate belt supports are installed in the space between the drive-storage unit and the tail section as the distance increases. When the stored belt is completely extended (about 60-foot advance of the tail section) more belt is spliced in and pulled into the drive-storage unit for further extension of the tail section. Since conventional belt is used, this system can operate only on a straight line and alignment of intermediate supports and the tail section with the drive-storage unit is important. To negotiate curves, multiple cascading units must be used which introduces undesirable transfer points. Heavy duty drive-storage units have been built that allowed up to 2000 feet of extension (11).

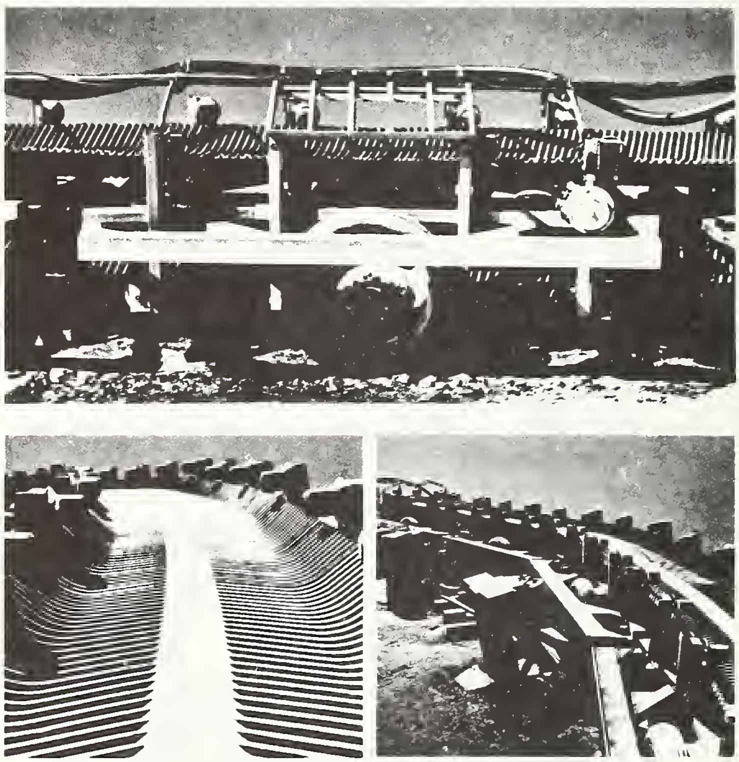
The Joy Serpentix Conveyor, based on a design developed in Germany, is made by Joy Manufacturing Company for use in underground bedded deposits. The Serpentix conveyor, in lengths from 200 to 400 feet, is supported from a monorail anchored to the roof. Power to move the conveyor unit forward and backward on the monorail is provided by a hydraulic power pack which also move on the monorail. The special design of the Serpentix belt and its supporting vertebrae spine assembly provide the flexibility required when the belt assembly goes around a turn or around the pulleys at either end of the assembly. The special belt design also allows the loaded and return flights of the belt to travel in the same horizontal plane rather than over-under as in conventional belt conveyors. The Serpentix belt is a series of molded neoprene pieces bolted together with brackets attached to the conveyor drive chain at eight-inch intervals. Each neoprene piece has a convoluted shape the width of the belt to form a pan and provide flexibility. This system is mechanically complex and expensive. It appears to have little potential application in tunnel construction.



COURTESY LONG-AIRDOX CO., OAK HILL, WV.

FIGURE 14. BRIDGE CONVEYOR - BRIDGE CARRIER SYSTEM

The Joy Flexible Conveyor Train (FCT) is based on a molded troughed belt system developed jointly by Joy Manufacturing Company and the B. F. Goodrich Company. Two versions, one mounted on a series of rubber tired dolleys (Figure 15) and the other monorail-mounted have been developed to the test stage. The entire 400-foot FCT is self-propelled by multiple drive units located at each end and at intermediate points. The molded "Serpentine" belt has a heavy center section embedded with steel tension cables. The side sections, which are troughed up from the center section at 45 degrees, are fluted to allow the edges of the belt to stretch when it moves around turns or passes over pulleys. The fluted sections of the belt are reinforced with wire inserts to maintain the cross section when the



Courtesy Joy Manufacturing Company

FIGURE 15. FLEXIBLE CONVEYOR TRAIN, WHEEL MOUNTED

belt edge bears against the guide rollers. The belt is designed to operate around horizontal curves down to 20-foot radius. At 600 fpm belt velocity the capacity is about 700 tph of coal.

The monorail-mounted transfer conveyor (Figure 16) has been used for a few short wall mining applications. It is a straight belt conveyor assembly that rides on a roof-hung monorail and is suspended above the panel belt. Installations have ranged in length from 100 to 200 feet, but the principle seems to be capable of extension to much greater length for application to straight tunnel projects. Or it could be developed as a series of suspended

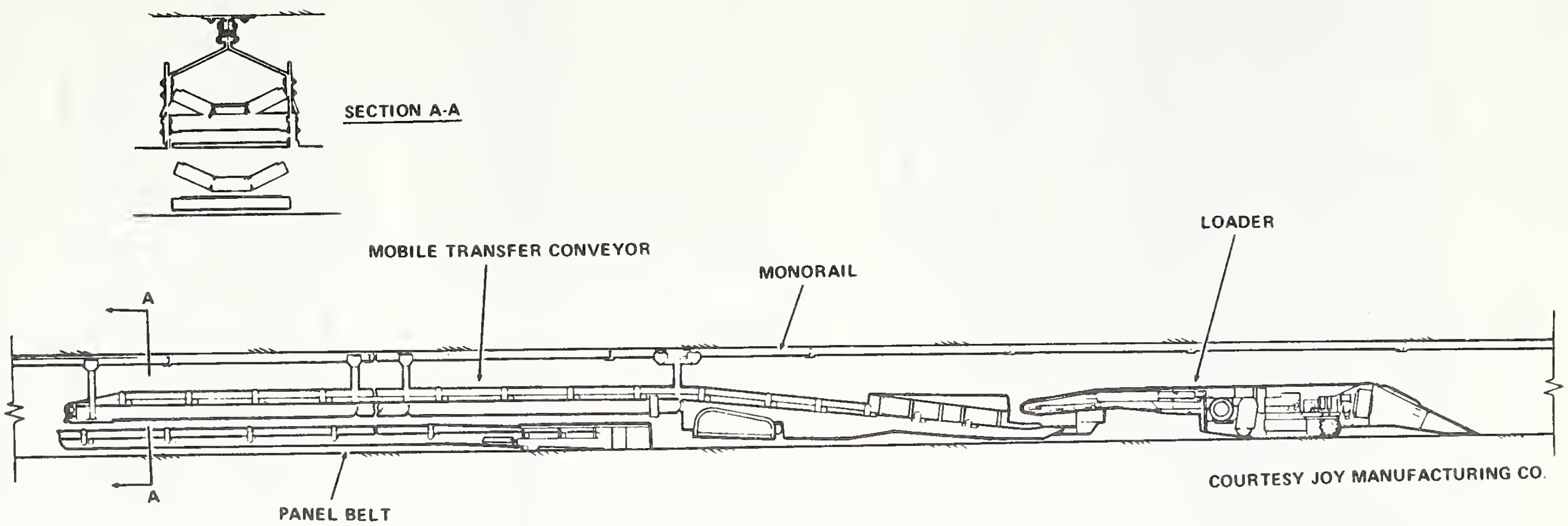


FIGURE 16. MONORAIL-MOUNTED TRANSFER CONVEYOR

shorter sections of bridge conveyor to permit negotiating curves as proposed in a Bureau of Mines Project (Reference 12, page 144).

Several cascading conveyor systems were designed and built in the early 1950s and 1960s, but very few remain in operation. These systems covered the range from the very expensive Moleveyor consisting of a string of shuttle car-like conveyor units to the much simpler, manhandled portable conveyor units of the Joy 2PC. However, in general the cascading systems were characterized by many short lengths of conveyor (about 20 feet each), many material transfer points, mechanical complexity, low capacity (about 400 tph maximum), a high degree of mobility and flexibility, and high investment and operating costs. There appear to be no features in these systems of particular interest for application to tunnel construction.

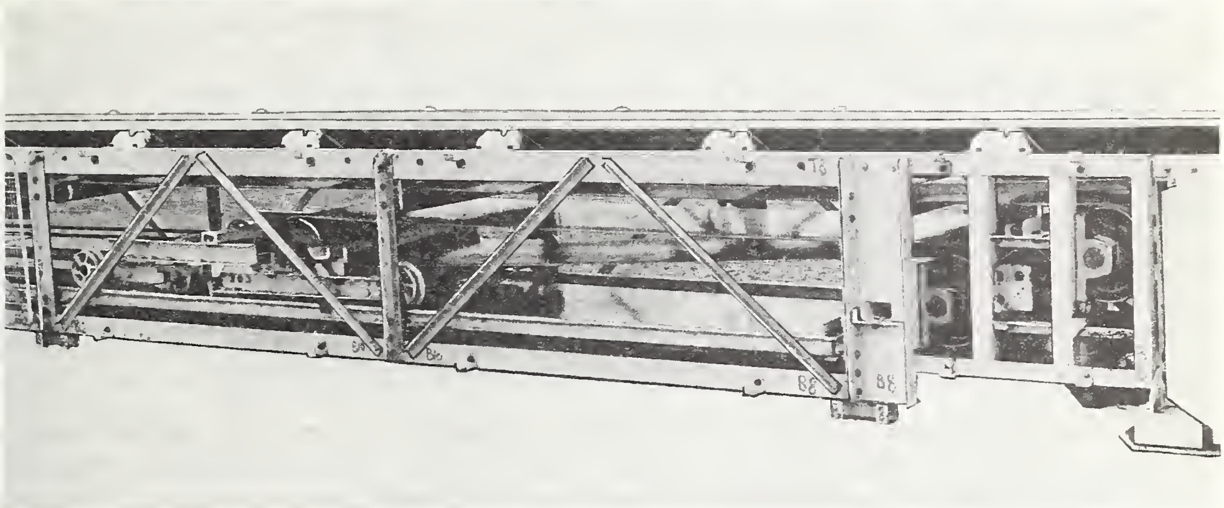
Extension in Tunnels

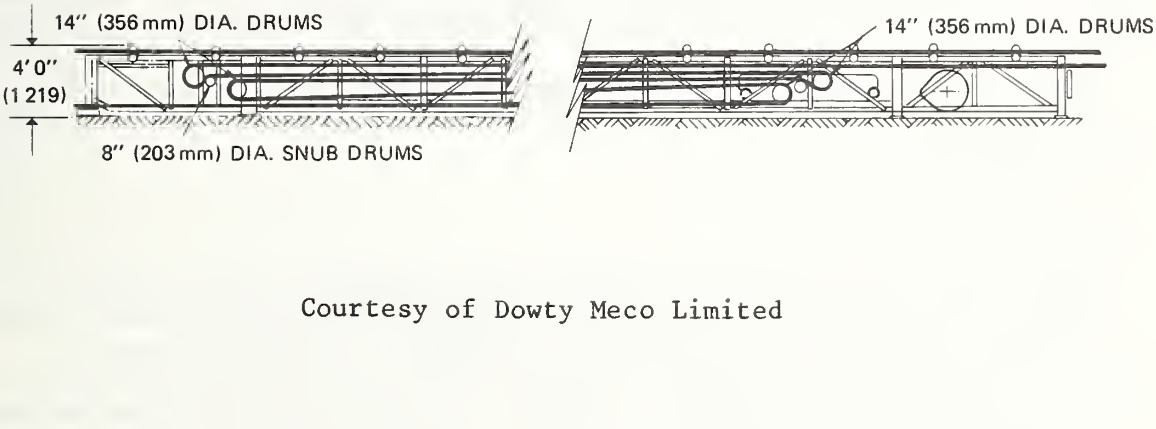
Faddick and Martin (28) discuss the use of extensible conveyor systems as a feeder system to a hydraulic muck transport system for tunnel construction. Their evaluation includes most of the systems reviewed by Cowan (11, 12) for coal mine applications. The conclusion was that a conveyor system with an acceptable service life could be inexpensively custom designed from available commercial components and provide the extensibility required for continuous tunnel muck haulage.

Much less system mobility is required for conveyor extension for tunnel construction than for coal mining. For multiple entry coal mining, the face haulage system must have the ability to advance and retract repetitiously up to 600 feet and to maneuver from one entry to another. To be practical, the system must be self-propelled with speeds up to 80 feet per minute. For tunnel construction, once the material handling system is extended it does not need to be retracted (except for minor distances at the heading), and the maximum rate of extension is 6 feet per minute. The maximum rate projected for system installation (in the far term period) is 600 feet per day (25 feet per hour). Therefore, it is not necessary to pay for the mobility designed into the coal mining systems. Belt conveyor extension concepts for tunnel construction should strive for maximum simplicity and minimum cost.

A relatively simple, stationary belt storage and extension unit as shown in Figure 17 might be adapted for tunnel application. The present maximum capability of these units is about 500 feet of belt storage (250 feet extension). However, there appears to be no fundamental principle to preclude development of much larger units in the range of a few thousand feet of belt storage. If a supply of belt sufficient for a five day advance of the mole could be stored, belt sections could be spliced into the system during the Saturday maintenance period. The average daily advance projected for the far term period is 300 feet. This would require storage of 4000 to 5000 feet of belt to assure no shutdown during the week for belt addition.

A belt storage unit for about 500 feet of belt is about 70 feet long by 55 inches high by 76 inches wide (34). The maximum unit required for tunnel construction might be 400 feet long and 8 feet high. If this proved to be impractical, two or more smaller units might be used in series.





Courtesy of Dowty Meco Limited

FIGURE 17. BELT STORAGE AND EXTENSION UNIT

The principles embodied in the bridge conveyor without the bridge carrier (Figure 14) or in the monorail-mounted transfer conveyor (Figure 16) appear adaptable in lower cost versions to meet the needs for short advance and retraction, and system installation at the heading.

Curves in Tunnels

The flexibility required for a material transport system for tunnel construction is much less than that required for multiple entry coal mining. In coal mining, the face haulage system must provide for forward and backward movement around multiple, short radius (less than 20 feet) curves and simultaneously for vertical movement to accommodate undulations and severe pitch in the floor and roof. In urban mass transit tunnels, the minimum radius curve is projected at 750 feet (1200-foot arc length for a 90 degree curve), and undulations and pitch in the tunnel are minimal.

Two developments, the garland idler (Figure 11) and the Serpentine belt used in the Flexible Conveyor Train (Figure 15), offer potential solutions to the problem of negotiating curves during tunnel construction. The garland idler has been used to guide a conventional belt around curves with radii down to 1200 feet (35). At least one manufacturer is investigating application of garland idlers to curves of shorter radii. In addition to improved belt guidance, these idlers can be mounted on structures that are quick to assemble and disassemble, easy to transport, and simple to aline. Quick release suspension is provided so faulty idlers can be dropped from service while the belt continues to run.

The Serpentine belt has proven its ability to operate on a more complex path than that required for urban transit tunnel construction. Cost reductions for the supporting structure should be achievable through design modification to meet the less stringent requirements of the tunnel situation.

The use of intermediate drives (Figures 12 and 13) to reduce belt tension also could contribute to the solution of the problem of belt conveyors on curves.

CONCLUSIONS

The advances which have been made in belt conveyors for horizontal transport of bulk materials have been in response to specific needs, primarily for overland conveying and for coal haulage in underground mines. The principal goals for overland conveying have been to increase system capacity, increase the transport distance of a single-flight conveyor, and to accommodate at lower cost the variable terrain of overland routes. This has resulted in the development of higher strength belting which can be operated at higher speeds, more powerful drive units, intermediate drive units, flexible idler assemblies, the wire rope support system, and the Cable Belt concept. Most of these advances also have been applied to main haulage systems in mining operations.

Face haulage in multiple entry coal mines presented different goals, specifically, a high degree of mobility and flexibility. This resulted in

the development of highly mobile, but expensive integrated systems which are generally overdesigned for the requirements of tunnel construction.

The application of a belt conveyor for transport of muck from the heading to the shaft or portal during tunnel construction presents a set of requirements different from those for overland conveying, face haulage of coal or mainline haulage of mined materials. Most of these requirements are less severe than their counterpart found in the other applications. It should, therefore, be possible to accommodate these requirements by applying (in less costly concepts) the principles used to meet the more severe requirements of the other applications. If this approach can be used successfully to solve the principal problems of system extension and operation around long radius curves, the application of a conveyor system for muck haulage in tunnel construction will be an alternative open to the contractor based on his preference and assessment of economic competitiveness.

7. CONVEYORS FOR ELEVATING

STATE OF DEVELOPMENT

The earliest form of conveyor used for continuous elevating of bulk materials is probably the bucket elevator. Apron conveyors which with special deep bucket designs can elevate on incline angles up to 60 degrees, also have been used in the steel and other heavy industries for many years. More recently, conventional belt conveyors have been used but their application has been limited by the low angle of rise and resulting long horizontal distance required. Design modifications, new concepts and improvements in materials have occurred which have made these systems more reliable and extended their range of applications.

At the 1977 Keystone Workshop on Materials Handling for Tunnel Construction (26) the panel reviewing elevators summarized the state of application of bucket elevators and belt conveyors to tunnel construction as follows:

> In general there has been a reluctance among tunnel contractors to utilize bucket elevators or elevating belt conveyors for the removal of tunnel muck. Until recently, the traditional method of muck removal has been by crane or hoist. Two tunnel projects now under construction are using bucket elevators for the first time in the industry.
>
> Bucket elevators have been used in many industrial applications. The construction industry poses a challenge in that the material is not always a constant product. Long tunnels intersect a variety of geological formations with varying properties including varying moisture content. The use of tunnel boring machines produces a more uniform end product which is easily adapted to continuous handling machinery.
>
> Proper sizing of material is the prime factor and materials from drill and blast operations could also be removed by these systems if the material could be sized correctly and efficiently.
>
> Development of the bucket elevator for mucking has been limited by the market. If the market were expanded, many of the present day problems associated with the use for tunneling would be solved by in-house development. Industry is reluctant to spend money for research in limited applications.
>
> Present day technology offers capacity of 300 to 400 tons per hour for lifts to 250 feet. Technology is available to increase these capabilities and lifts given the proper incentive.

Discharging of sticky material is the principal problem and has a questionable chance of being solved for clays but a good chance for rock in the short term. This problem is less severe in belt elevating systems.

All projects require careful investigation as to whether substantially standard systems can be used.

Belt systems are available in slight variations utilizing rubber belts of varying configurations. Flexowall, Beltavators and others use different configurations to accomplish the same function as bucket elevators. Sizing of the material is also required.

In addition to the recent installation of bucket elevators for the removal of tunnel muck, one tunnel contractor has installed an inclined conventional belt system on a 300-foot lift to handle 1000 tons per hour of muck from two moles operating simultaneously, and an inclined haulage belt has been installed on a 15 degree rise to elevate ore 1,900 feet with two 3,700-foot flights.

Comments heard from industry sources during a series of interviews conducted by Holmes & Narver, Inc. (33) and at the Keystone Workshop (91) include:

a. An important requirement to be met by an elevating system for muck haulage is to have the ability to handle a wide range of material characteristics for a single application, that is, to be rather insensitive to material properties.

b. A proper continuous material handling system should not require continuous maintenance.

c. Muck haulage up the shaft is the most critical material handling problem. A bucket elevator has possibilities for this application.

d. Exotic conveyor systems may prove to be economically advantageous for vertical shaft haulage. Spiral conveyors may be developed that can be installed at a lower cost than a headframe-skip combination. A Ferris wheel type bucket conveyor is at work on the Desourdy project in Montreal.

e. The next cost-saving advance in material handling for tunneling may be in continuous vertical haulage, but the track record that will induce wide acceptance does not yet exist.

f. The limiting factors for present, continuous vertical haulage systems are:

(1) Capacity of 300 to 400 tph.

(2) Lift height up to 250 feet.

(3) Material density of about 110 pounds per cubic foot.

(4) Less than 15 percent of volume as maximum lumps of 8-inch size.

g. The chance of achieving, in the long term, double the current capacity of continuous elevating systems appears to be good.

h. The muck particle size limits the application of all continuous elevating systems. Unless sizing techniques are used so the conveying system is fed a uniform size material at a steady rate not exceeding design capacity, continuous elevating systems cannot be used for drill and shoot operations. Low profile crushing equipment should be investigated.

BUCKET ELEVATORS

Conventional Bucket Elevators

Gumz (30) recently reviewed the fundamentals of conventional bucket elevators with particular emphasis on their application to tunneling projects. Some of the highlights of his discussion follow.

All elevators are volumetric units so that for a given set of components and speed of operation the volumetric capacity is constant. The mass capacity (tonnage), therefore, varies as the density of the material being handled.

There are four basic types of bucket elevators but the Super-Capacity elevator is best suited to muck handling for tunneling projects. The Super-Capacity elevator with its extra large buckets mounted between two strands of chain is suitable for handling lump sizes up to 8 inches while operating at speeds in the range of 125 to 150 fpm. The buckets vary in width from 16 to 48 inches giving capacities from 325 tph to 1000 tph for material of 100 pounds per cubic foot density. Height ranges from 75 to 150 feet are in industrial service.

The characteristics of the material to be handled are very important in the selection of elevator components and types. Tunnel muck is not an average bulk material and, therefore, requires consideration of special materials of construction, speed and bucket design. Material sluggishness or stickiness, often found in tunnel muck, can create difficult problems with bucket elevators.

Maximum lump size is an important consideration in selecting bucket size. A valid rule of thumb states that the maximum lump should not exceed approximately two-thirds of the bucket projection, and that the bucket length should be at least three times the maximum lump if the large lumps constitute 10 percent or more of the material.

The continuously welded, dust tight, steel casing of the elevator is self-supporting, that is, it transmits the entire load from the headshaft

to the base of the elevator. This does not mean, however, that it is free standing. The casing must be supported laterally at about 20-foot intervals to maintain vertical alignment for proper operation.

The most critical component in determination of tonnage capacity and lift height of a bucket elevator is the chain tension member. These chains must have the tensile strength, fatigue life and reliability to provide the optimum hours of service under full load with minimum downtime for maintenance. The hardness of the chain particularly in the articulating joints must be greater than that of the material being handled to assure long chain life and good reliability.

Modern commercially available all steel chains are rated for about 20,000 pounds to achieve a minimum fatigue life of 40,000 hours.

A fixed load rating results in decreasing bucket size as the lift height increases, to maintain a constant load on the chains. For constant speed and material density, this means the capacity decreases as the lift height increases. Since the chains are designed to wear out rather than break (the ultimate strength far exceeds the load rating) additional capacity can be obtained by reducing the rated life of the chain. That is, the chain can carry a greater load but the fatigue life will be shortened. By limiting the fatigue life of the chain to a single job (with adequate margin of safety), commercially available bucket elevators can be designed in a single lift configuration for the lift heights and muck rates required for current tunnel projects.

Attempts to increase capacity by enlarging the chain are self-defeating as the mass of the chain becomes an ever larger portion of the load supported by the chain. However, through development of better materials and fabrication techniques, a chain has been developed and a prototype tested which established a working load of 50,000 pounds per strand. Commercial production has not begun as the market for this more expensive chain has not been identified.

Projected muck rates and lift heights for the far term period exceed the capability of single lift bucket elevators with currently available commercial chain. Elevating systems based on chain with higher rating, such as the 50,000-pound prototype, or cascading elevators would be required to meet the needs of the far term period. The use of cascading elevators is undesirable because it places a transfer point and head-end drive unit near the midpoint of the shaft (a difficult location for proper maintenance). Another approach might be the development of an intermediate drive unit to reduce chain tension.

Two bucket elevator installations have been made for muck lifting on tunnel projects. One has a system design capacity of 300 tph (system capability of 400 tph) at 175-foot centers; the other, 250 tph design capacity (350 tph capability) at 230-foot centers.

For a system with 36-inch buckets handling 110 pounds per cubic foot material crushed to minus 8-inch, with the system expected to last for only

one job, the capacity based on near term technology would be 600 tph for a center-to-center lift of 90 feet and 400 tph for a 250-foot lift. Far term technology is anticipated to provide a capacity of 800 tph for a 200-foot center-to-center lift.

The advantages of a bucket elevator for removing muck from a tunneling operation are:

a. The material can be continuously handled, usually at a rate exceeding, for relatively low lifts, other methods exclusive of the belt conveyor.

b. The bucket elevator in a shaft brings the muck to the surface in the shortest distance between the invert and the surface.

c. These machines are compact in cross section and take up a minimum amount of room in the shaft, allowing for other lifting and lowering functions to continue, while conveying the muck to the surface.

d. The horsepower per ton of material handled will be lower or compare favorably with other means of haulage.

e. Additional excavation for equipment installation is minimal.

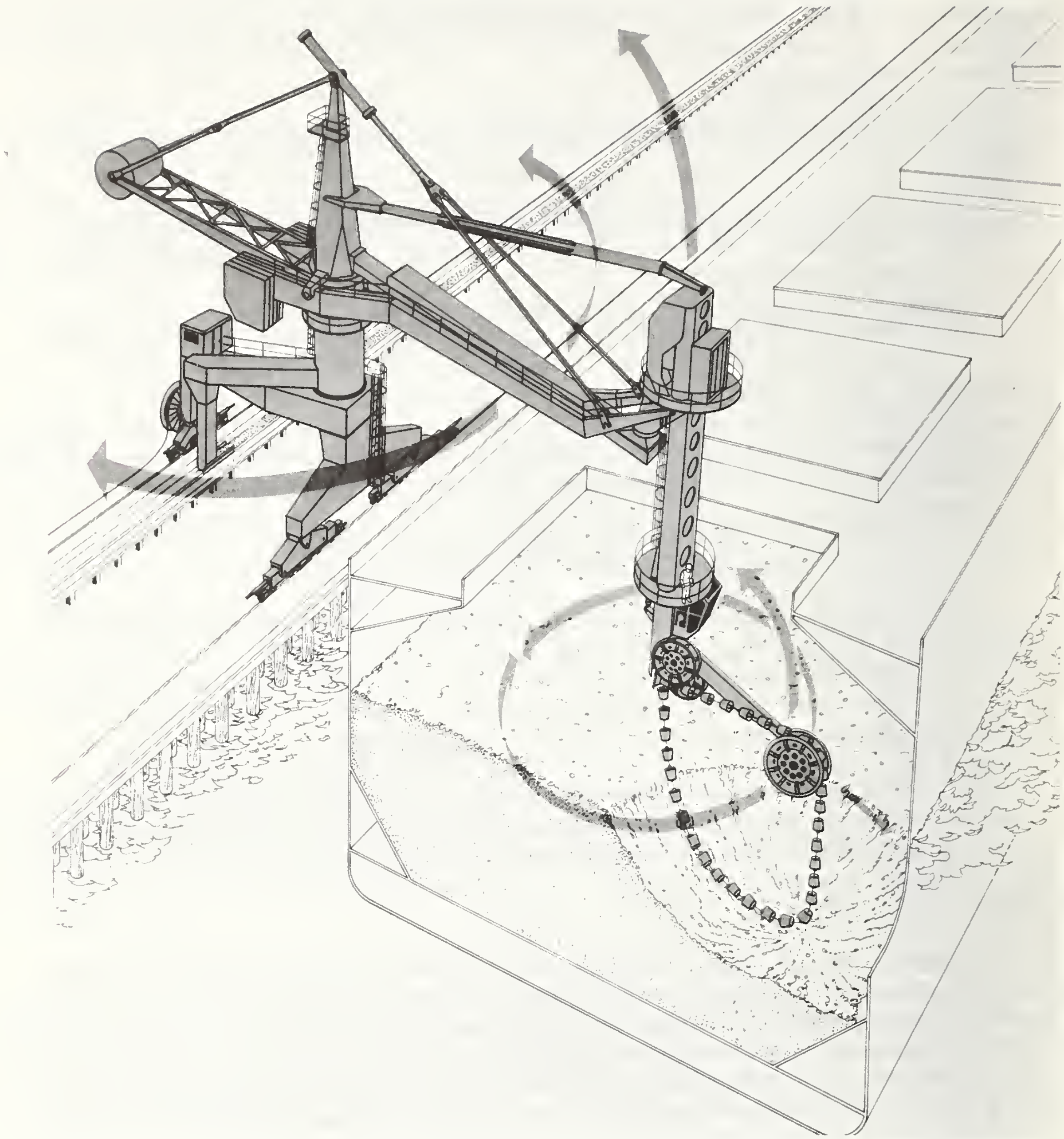
f. Capital costs of an elevator and its backup system will usually be lower than other lifting methods within the height limitation of the elevator.

g. The structurals, drive, and terminals will conceivably outlast the tension members, so a given elevator could be rechained and either lengthened or shortened (within limits) for use on another project.

Novel Bucket Elevator

A unique design for a true "bucket" elevator is shown in Figure 18. This continuous unloader consists of an endless string of heavy duty steel buckets connected by a wire rope passing through the center of each bucket. Special sprockets are used to drive the string of buckets at high speed as they dig into and fill with any free flowing material. The PACECO system will handle 1800 tph with 24-inch buckets traveling at 600 fpm in free flowing, free digging material.

Although the system was developed and is used for bulk carrier unloading and stock pile reclaiming, a preliminary concept for lifting muck from a shaft pocket has been initiated. Some potential difficulty with loading and unloading this system can be anticipated due to the sticky, nonflowing character of many muck piles. If satisfactory loading and unloading of typical muck can be demonstrated, the system could eliminate the need for the transfer and loading equipment required with a conventional bucket elevator. Cost reductions probably could be obtained by elimination of some of the mobility indicated in Figure 18.



Courtesy of PACECO, Inc. (62)

FIGURE 18. PACECO CONTINUOUS UNLOADER

Comments from Industry

Comments regarding bucket elevators heard from industry representatives during a series of interviews conducted by Holmes & Narver, Inc. (33) and at the Keystone Workshop (91) include:

a. Bucket elevators work fine on dry material, but with wet material and no special unloading features, the material is difficult to unload. The uncertainty and variability of the material characteristics make muck handling a doubtful application.

b. Bucket elevators were considered for the job but were rejected because of the sticky muck to be handled. Sticky clay always causes a headache.

c. All bucket elevator manufacturers have tried to produce slick surfaces to solve the sticky material problem, but you must also take care of the abrasion. Rappers have been tried to dislodge the material. These attempts to solve the problems have been uncoordinated in the industry.

d. The buckets could be "knuckled" over the head pulley to provide a longer time for dumping while using a free release surface material. Larger buckets could be used so the amount of material sticking would be a smaller portion of the total load.

e. Bucket elevators are not good because there are too many maintenance problems and maintenance costs are high.

f. The bucket elevator cannot handle large pieces. The feeding equipment also causes problems.

g. Bucket elevators can handle lumps up to 10 inches if they are less than 15 percent of the total material.

h. Everyone in the tunneling industry has talked about bucket elevators and the problem of stiçky material and other vague problems. The key to bucket elevator use is to install, apply and maintain them properly, and to control the feed to the elevator. A bucket elevator is not a good choice for a sticky material. The elevator manufacturers are not sitting still. The state of the art is advancing. They are looking at better materials to get bigger capacities.

i. To obtain good performance from a bucket elevator it must be installed, operated and maintained properly. Contractors often do not do this. As much time should be allocated to material handling system maintenance as spent on the mole. Maintenance "musts" include:

(1) Torque bolts to specified amount and retorque after run in.

(2) Control lump size in feed material.

(3) Do not operate with missing buckets.

(4) Keep the boot clean. The buckets are not designed to load out of the boot.

(5) Provide maintenance when needed.

j. Using belt rather than chain as the transporting medium for a bucket elevator seems impractical. So much steel cord would be required in the belt that it would be difficult to get the attaching bolts between the cords. Use of wire rope seems more practical and should be investigated.

INCLINED CONVEYORS

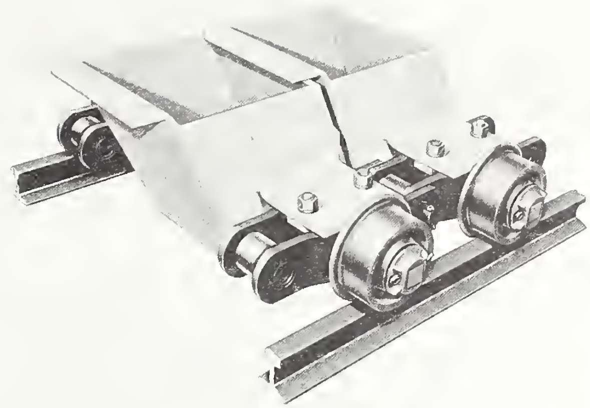
Conveyors for elevating bulk materials on an incline are of two basic types; those using chain as the transporting medium, and those based on a conveyor belt as the tension member.

Chain Driven Conveyors

There are two types of conveyor based on an endless chain to transmit the motive power. One concept, known as an apron conveyor, is shown in one of its various configurations in Figure 19. This concept has pans or buckets supported on or between two endless chains which travel on wheels on light weight rails. Apron conveyors have been in use for many years as elevators and feeders in many types of industry. The bucket configurations have been used successfully on inclines up to 60 degrees. A 36-inch wide conveyor handling 100-pounds-per-cubic-foot material would have a capacity of about 500 tph on a 30-degree incline or 375 tph at 60 degrees. The largest apron conveyor commonly used (60-inch width) has capacities of 800 tph at 30 degrees and 600 tph at 60 degrees. Maximum practical speeds for these conveyors are about 115 feet per minute.

The other basic type of chain conveyor uses a chain, usually single strand, fitted with cross bars, plates or other conveying elements to drag the bulk material through an open trough or an enclosed casing. The material moves as a continuous mass at the same speed as the conveying elements. The open trough drag chain conveyors are restricted to relatively low angles of rise but the enclosed type is used extensively for transport of fine mesh materials in horizontal, inclined or vertical attitudes, or in combinations of attitude in a single system. These systems have capacities up to 300 tph for a 23-inch conveyor.

The ruggedly constructed open trough conveyors are frequently used as armored face conveyors for longwall coal mining. The enclosed drag conveyors are especially suitable for handling fine mesh materials that might cause dusting problems with open conveyors. The transport distance



Courtesy of Rexnord (68)

FIGURE 19. APRON CONVEYOR

and capacity of these conveyors is limited by the strength of the chain tension members and practical maximum speeds around 200 feet per minute. The all steel construction of apron and chain conveyors makes them suitable for transporting materials at temperatures greater than those tolerated by belt conveyors.

Due to the limitation imposed on capacity by practical speeds and chain strength, the mechanical complexity, and cost, chain driven conveyors have not been proposed for elevating tunnel muck from the invert to the surface. However, apron conveyors have been installed as feeders for grizzlies on tunneling jobs. Some have been considered unsatisfactory because of excessive maintenance and dirtiness. This application is usually less than 100 feet in length with a rise less than 15 feet.

Belt Conveyors

Since the earliest applications of belt conveyors, attempts have been made to use them for elevating bulk materials. The first attempts supported the conveyor by a straight rigid frame and raised the head pulley until material began to tumble back down the incline. The limiting angle of incline for most materials was found to be 15 to 18 degrees when conventional troughed belts are used. For a 15-degree rise, the material is discharged at a horizontal distance from the feed of 3.7 times the height of rise.

To obtain greater angles of inclination, a heavy cover belt, traveling at the same speed as the conveyor, was placed on the load (while being elevated) to increase the friction coefficient and prevent sliding and spillage of the material. The cover belt permitted elevating at an angle of

45 degrees. This reduced the horizontal distance between the feed and discharge points to about the height of the lift.

These steep-angle conveyor belts with angles between 35 and 38 degrees were used for many years on bucket wheel excavators removing overburden for surface mining operations (50). They also have been used more recently in a mobile bridge configuration operating at 40 to 45 degrees in open pit mining operations. A 60-inch wide overlay belt system operating at 750 feet per minute could elevate 6,000 tons of material per hour.

An overlay steep-angle conveyor belt has not been used for underground excavation in the United States. However, a conventional belt installation has been made in a 15-degree decline designed to lift 1400 tph of copper ore from a depth of 1,900 feet in two flights of 3,700 feet each. These 1-1/8-inch thick by 42-inch wide belts driven by 1,800 horsepower motors can operate at 662 feet per minute. The belt is hung from the back of the decline with turnbuckles on 10-foot centers. Troughing idlers are on 10-foot centers and return idlers on 20-foot centers. The major reason for hanging from the back is to facilitate spillage cleanup. There has been very little spillage, mostly fines. No spray is needed for dust control with the 6 percent moisture material handled. No material tends to roll or slide downhill on the belt.

A conventional belt inclined conveyor, designed for 1000 tph, has been installed in an 8x8-foot horseshoe, 20-degree decline. This system has a 36-inch wide belt fed from two moles operating simultaneously through a rotary car dump, a vibratory apron feeder, a grizzly, a crusher and a feeder belt. A large pocket, approximately 20x20x20 feet, was excavated to accommodate this sizing and feed equipment.

Comments regarding inclined belt conveyors heard from industry sources during a series of interviews conducted by Holmes & Narver, Inc. (33) or at the Keystone Workshop (91) include:

a. Sinking a 15-degree decline is hazardous. We had one fatality and several close calls. We probably would not sink another decline.

b. An inclined tunnel for an inclined belt system is quite expensive.

c. Although this tunnel contractor is using an inclined conveyor, he probably would not use it on another job.

d. An inclined conveyor is a time-consuming and expensive installation. It requires sinking the decline, supporting the ground, installation of the conveyor, and backfill after removal of the conveyor.

e. Slant shafts should be considered for general tunnel support. They could be used during construction for inclined transport of materials.

f. It is dreaming to think about putting in slant tunnels for metropolitan sites. You cannot afford the real estate.

g. You cannot beat an inclined conveyor for vertical muck haul if the right-of-way is available. The inclined tunnel could be used for a permanent vent shaft.

h. If space is available and there is enough muck to warrant the investment, an incline provides continuous haulage with the dependability of a conveyor and the advantage of leaving the main service shaft free for transport of men and materials.

i. In general, for coal mines, inclined conveyors on a 16- or 17-degree slope or inclined hoists are used for less than 600- to 700-foot depth. Vertical hoists are used for greater depth.

j. A rule of thumb is: Use a conveyor in a decline rather than a hoist if the depth is less than 400 feet.

k. Several studies of conveyors in declines versus hoists in vertical shafts have indicated that for less than 1500 feet use the decline; for deeper than 1500 feet use the hoist.

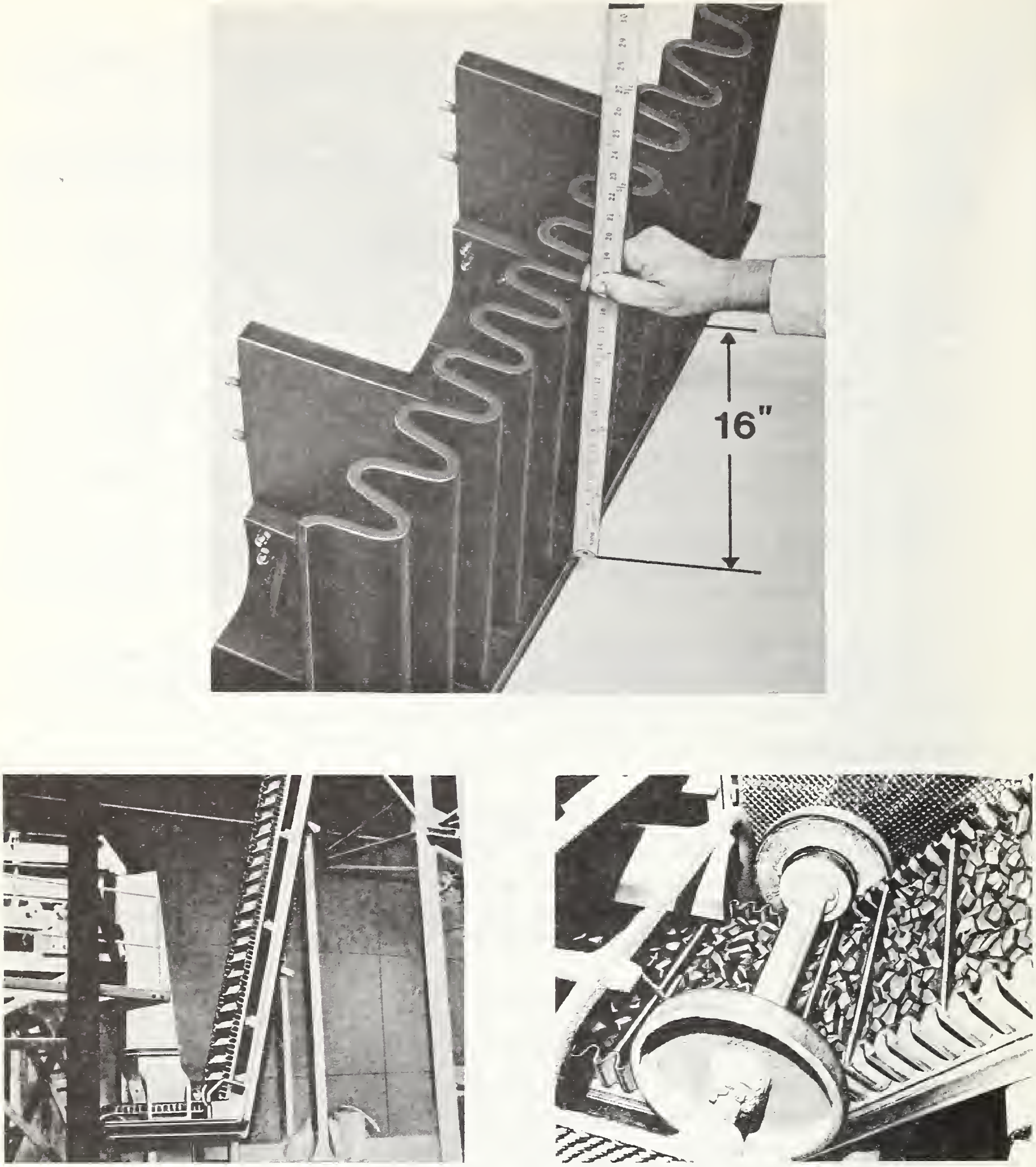
l. At Lakeshore the decline conveyor beat the hoist on the basis of economics for a depth of about 2000 feet and production of 10,000 to 15,000 tons per day.

FLEXOWALL CONVEYOR

A unique concept known as the Flexowall* conveyor, shown in Figure 20, was introduced in 1963 to obtain steeper incline angles than practical with conventional belts. This concept is based on a special belt design which includes fluted sidewalls and cross walls or cleats to form pockets on the belt. The cleats are bolted to the sidewalls and to rubber angles vulcanized to the belt. Splices are vulcanized to provide a very quiet running belt.

Sidewalls from 2 to 16 inches can be used for various angles of incline and capacities. With the 16-inch wall, which has been developed but not introduced commercially, capacities in excess of 10,000 tph can be obtained. The belts can be run at speeds up to 1000 feet per minute, but most installations run at only a few hundred feet per minute. Pretensioned steel cords

*Registered tradename of the Flexowall Corporation (a Scholtz Company), One Heritage Park, Clinton, CT 06413.



Courtesy of Flexowall Corporation

FIGURE 20. FLEXOWALL CONVEYOR

are used as tension members in the base belting. The flat base belt requires only flat idlers, eliminating the more expensive troughed idlers.

There are over 10,000 Flexowall belt installations around the world in a wide variety of industries. The most frequent application is for elevating material up an incline which can be up to 80 degrees. However, a maximum incline of 45 degrees in usually recommended because the decrease in capacity for steeper angles is not offset by the saving in conveyor belt length. When horizontal space is at a premium, as in a shaft, steeper angles might be economical. For an 80-degree incline the horizontal distance required is less than 18 percent of the rise.

Steeper inclines require higher sidewalls, closer spacing of the cleats and wider belt to maintain capacity. Less incline means longer belt, more supporting structure and more horizontal space. A design objective is to balance these factors to achieve minimum cost.

A concept using a cover belt to permit very steep angles, up to 90 degrees, has been developed, but the system has not been tested sufficiently for commercial introduction. Other developments include an improved belt design which permits wider belts and increased capacity.

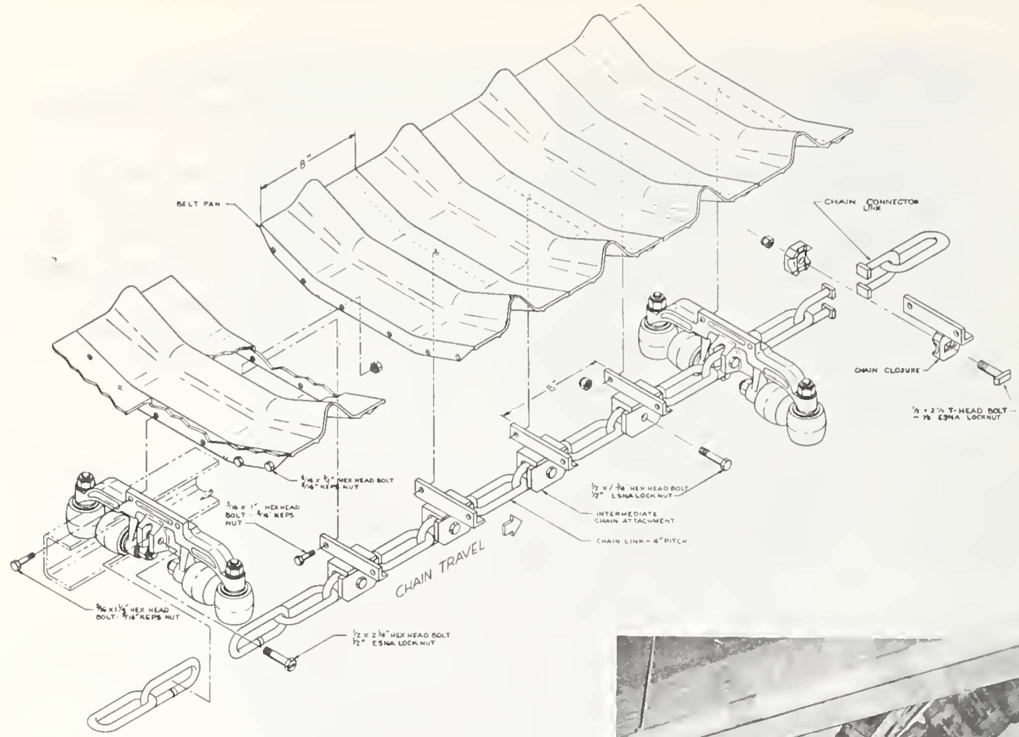
One disadvantage of the high quality Flexowall belt is its relatively high cost ($115 to $500 dollars per foot) compared to conventional belts.

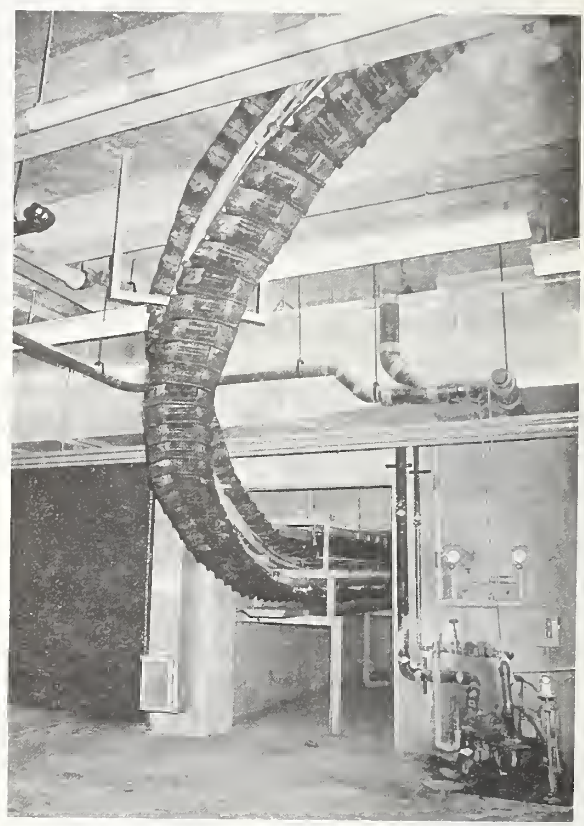
A typical Flexowall installation to handle limestone has a 54-inch wide belt, with pockets 24x50x12 inches deep, running at 200 feet per minute to elevate 500 tph of 90 lb/cf material 50 feet on a 45-degree incline using a 50 horsepower drive. The 1-1/8-inch base belt is supported by single flat load idlers on 20-inch centers and double flat return idlers at 40-inch centers. Long flat slabs up to 16x8x4 inches can be handled. The only problem encountered has been some loosening of side bolts during initial operation.

SERPENTIX CONVEYOR

The Serpentix* shown in Figure 21 is a chain conveyor similar in principal to the apron conveyor, that is, pans propelled by an endless chain are supported and carried by rollers moving on a fixed guideway. However, many differences in detail can be seen by comparing Figures 21 and 19. The Serpentix is driven by a single link chain at the centerline of the conveyor rather than two roller chains; it has guide wheels as well as load bearing wheels running in a channel; and the pans are made from molded

*Serpentix Conveyor Corporation, 1550 South Pearl Street, Denver, CO 80210.





Courtesy of Serpentix Conveyor Corporation

FIGURE 21. SERPENTIX CONVEYOR

rubber sections bolted together to form a continuous conveying surface. These features give the Serpentix its unique capability of extreme flexibility. A single section of Serpentix conveyor can make several continuous short radius turns, climb steep inclines and side dump material at any point along the route. This flexibility is the outstanding feature of the concept.

Over 600 installations of Serpentix conveyors have been made throughout the world since its introduction more than 15 years ago. Most of these installations have been relatively low capacity (less than 200 tph), short distance (less than 300 feet) systems with flexibility requirements which only the Serpentix could meet.

The flexibility of the Serpentix permits it to make 180-degree turns in a single plane, to turn in a radius as small as 7 feet and to climb on a spiral with a slope as high as 40 degrees without load slippage. With special pockets attached to the Serpentix belt, material can be lifted on inclines from 60 degrees to nearly 90 degrees, but belts cannot be scraped clean when cleats are attached. Flight lengths of about 1000 feet are the longest practical.

Like other chain conveyors, the capacity, flight length, lift height, and incline angle are interrelated and determined by the strength of the chain. The largest Serpentix belt is 40 inches wide. This provides a capacity of 700 tph when running horizontally at 210 fpm with 110 lb/cf material. The capacity is reduced about 50 percent when operating on a 60-degree incline. The belt speed is limited to less than 300 fpm by the link chain drive.

Several years ago two Serpentix units capable of turning on a 400-foot radius were installed on tunnel jobs to transport muck from the face to the rail car loading points. Some difficulty with belt cleaning was encountered on one of the jobs due to the wet, muddy shale handled. Maintenance costs resulting from loosening of bolted parts and wear of the chain, wheels and runners were considered to be high.

The Serpentix is a special type of conveyor for special applications. It cannot compete economically with conventional belts for routine requirements. It can be the solution to special problems where its capital cost and maintenance cost can be justified. The capital cost ranges from about 600 dollars per foot for a 24-inch width with a capacity of 150 tph (110 lbs/cf) to over 1000 dollars per foot for a 40-inch width with a capacity of about 400 tph.

The estimated life of key components is relatively short compared to the 40,000-hour design life for bucket elevator chain. For example, chain life is estimated at 8000 hours minimum, load rollers are lubricated for 10,000-hour life, and belt pan life is estimated to be 15,000 to 20,000 hours.

The Serpentix concept is not considered to be fully developed. Improvements are being developed for higher speed chain (up to 600 fpm), to reduce headroom required, and to reduce capital cost and maintenance.

THE BELTAVATOR

The Beltavator* shown in Figure 22 achieves the ultimate angle of inclination (90 degrees) for elevating bulk materials, by applying the principle of the cover belt, while using conventional conveyor belts. This concept has evolved through a series of developments starting many years ago with increased angles of inclination up to the maximum of about 18 degrees for conventional belts (72). This was followed by:

a. Cleated belts with side edges to prevent material from falling or rolling back.

b. A cover belt on a cleated belt to allow steeper slope (used in the cement industry).

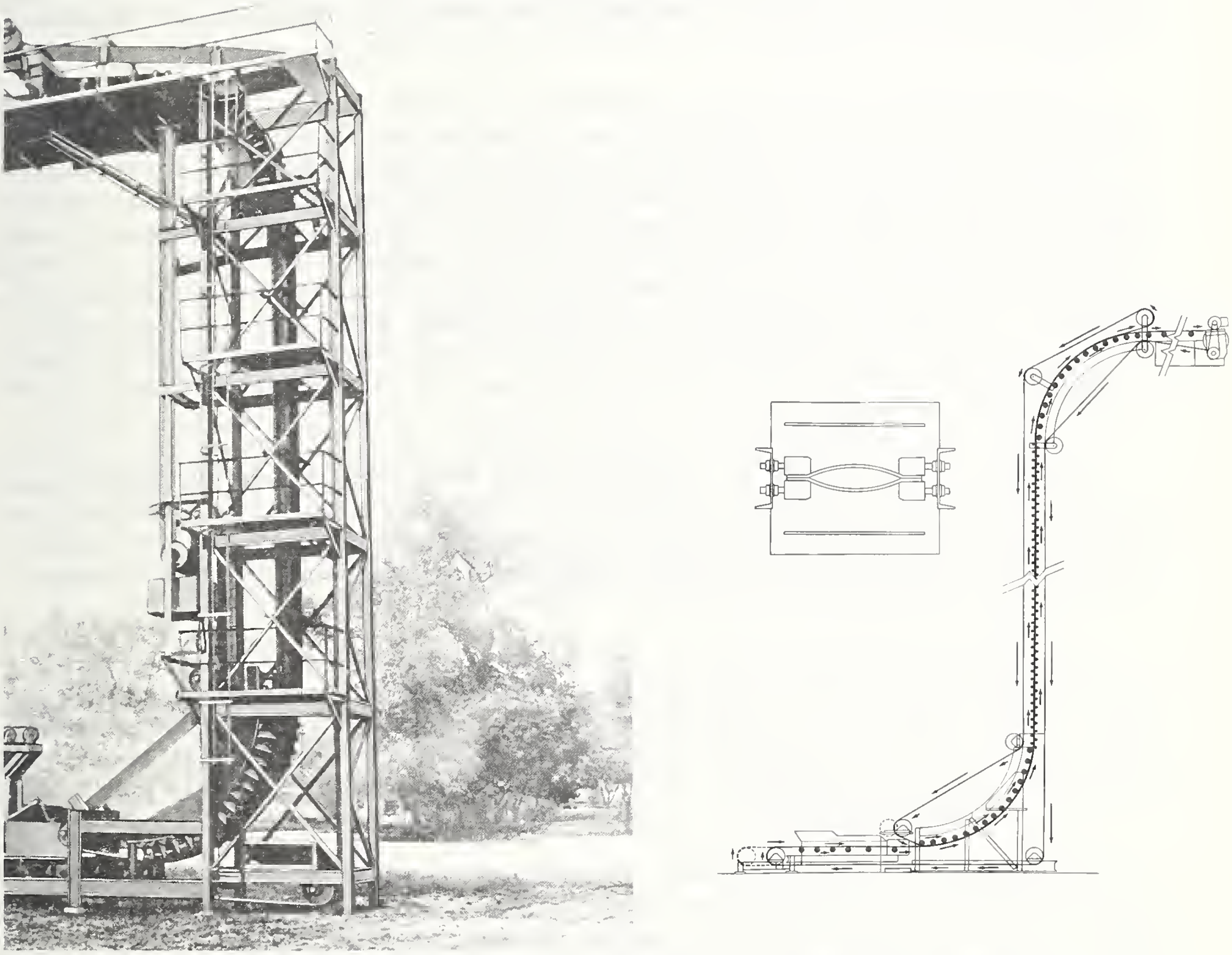
c. A retainer belt used with a conventional belt to reduce cost while allowing inclines up to 45 degrees.

d. The Loop Belt* using the retainer belt principle to elevate in the form of a "C".

e. The Beltavator using the retainer belt principle to elevate on a vertical path.

The Loop Belt, initially introduced commercially in 1971 for unloading bulk carriers on the Great Lakes, has proven capable of handling up to 10,000 tph of iron ore pellets or limestone. One installation, with a capacity of 7000 tph at a belt speed of 850 feet per minute uses a 78-inch wide belt and an 84-inch cover belt (the cover belt is always 6 inches wider than the carrying belt). The 78-inch belt runs the entire 550-foot length of the hold beneath a series of hoppers which dump through about 75 gates onto the belt. At the end of the line of hoppers the 84-inch cover belt covers the 78-inch belt thus holding the material between the two belts as they move upward in a long radius "C" curve. The belts travelling in the curve are held together by belt tension working against a series of slightly troughed idlers, closely spaced over the entire inside arc of the "C" path. At the top of the "C", the material is transferred to the 84-inch belt which dumps it through a chute onto a 60-inch belt mounted on a boom which can be

*Tradename of the Stephens-Adamson Division, Allis Chalmers Company, Franklin Street, Belleville, Ontario, Canada K8N5C8.



Courtesy of Stephens-Adamson Division, Allis Chalmers Company

FIGURE 22. THE BELTAVATOR CONVEYOR

swung through about 180 degrees to unload from either side of the ship. Because of the high tension used to keep the belts sealed, substantial structural members are needed on the inside of the "C" to resist the force of the belt.

The horizontal distance required for intallation of the loop belt, when designed on a half-circle "C" path, is at least one-half the height of elevation. This horizontal distance can be shortened by flattening the back of the "C" to form a "D" path but this does not decrease the amount of structural support required. At best, when used in a shaft, the horizontal space required and the structural support would completely block the center segment of the shaft and would to some degree obstruct the side segments. The Beltavator which requires much less structural support and horizontal distance would leave most of the shaft area open for transport of men and equipment.

The Beltavator uses the same tension principle as the Loop Belt to obtain belt sealing in the ingoing and outgoing arc sections of the travel path. In the straight vertical path, belt sealing is obtained by two series of side rollers (seen in the insert of Figure 22) which hold the belt edges together. The lateral stiffness of the belts causes an inward force at the centers of the belts. This holds the material between the belts so it does not slip downward even when the movement of the loaded belt is stopped. The decrease in lateral stiffness as the belt becomes wider (for a fixed belt thickness) limits the Beltavator to about 30-inch belts (for belts of practical thickness) unless some form of external side supports are used at the centerline of the belts.

Commercial application of the Beltavator has been limited although a 46-foot high demonstration unit with a 30-inch belt running at 650 feet per minute has proven the working principles of the system, and the Loop Belts unloading bulk materials from ships have handled millions of tons of material with no replacement of parts or belts.

The height limitation for the Beltavator has not been demonstrated but it is thought that with a 30-inch belt, 300 to 350 feet may be the practical limit. This would be adequate for the projected far term conditions. A 30-inch Beltavator to elevate 450 tph up to 300 feet would cost about 600 dollars per foot of elevation. Higher capacities (up to 850 tph) could be obtained for lower elevation distances and higher belt speeds.

The capacity of the Beltavator is about 80 percent of that for a horizontal belt of the same width and belt speed. As the horizontal belt carries about 81 percent of the material which can be placed on the belt based on the angle of repose, the carrying capacity of the Beltavator is about 64 percent of the theoretical capacity of the belt.

The Beltavator has successfully demonstrated the ability to handle wet, sticky materials and lump sizes up to 8 or 10 inches. If oversize lumps force the belt edges from between the side rollers, the load is spilled, but

the belt is not damaged. About one hour per 25-foot length is required to put the belt back in operation. Sticky clays and an 18-percent-moisture copper concentrate have been handled without difficulty. The wettest rock from a tunneling job should create no problem for the Beltavator.

If the horizontal run required is more than a few hundred feet, separate belts should be used for the horizontal run and the Beltavator. This is because the belt tension is much greater in the Beltavator than that required for the horizontal run.

The sealed bearings of the Beltavator rollers have a design life of 30,000 hours. Although the maintenance cost of a Beltavator will probably be slightly higher than a conventional horizontal belt system, it will probably be less than for most other methods of lifting bulk materials.

CONCLUSIONS

Bucket elevators have difficulty releasing wet, sticky materials encountered in tunnel muck. They also are height-capacity limited for a single flight by current commercial chain to something less than that projected for the far term case. Conventional inclined belt conveyors require excavation of long auxiliary inclined tunnels. Flexowall and Serpentix conveyors use expensive special belts and the capacity of the Serpentix falls short of the far term requirements.

The Beltavator appears to overcome most of these problems although its ability to achieve the far term height-capacity requirement has not been demonstrated.

8. HYDRAULIC TRANSPORT SYSTEMS

OVERLAND SLURRY TRANSPORT

Hydraulic transport of solids is becoming widely accepted throughout the world as a very efficient and economic method for continuously moving large volumes of bulk solids long distances for long periods of time. For these applications hydraulic systems are capital intensive with about 70 percent of the costs related to capital investment. Thus, transport rates are affected by the impact of inflation on the remaining 30 percent of costs less than the effect on railroad rates which are over 50 percent inflation sensitive.

The widespread interest in long distance slurry transport is based on several years of successful operation of systems such as the 53-mile, 9-inch diameter line installed in Tasmania in 1967 to carry 2.3 million tons of magnetite concentrate per year and the Black Mesa coal system which has transported 4.8 million tons per year since 1970 in an 18-inch diameter, 273 mile line.

One of the most recently constructed, and said to be the world's largest capacity long distance slurry pipeline (76), is the Samarco system transporting 12 million tons per year (1400 tph) of iron ore concentrate slurry in Brazil. This 246 mile, 20-inch line has a net elevation decrease of nearly 3300 feet from the mine to the terminal. The slurry is 62 to 65 percent solids with particle size of 85 percent minus 325 mesh and 3 percent plus 200 mesh. The minimum velocity is 5.2 feet per second.

Other large systems in the planning stage include a 38-inch diameter line to transport 25 million tons per year of coal for more than 1000 miles. In most long distance applications, the solid particles are very small. Fourteen mesh (about 1.5 mm) is a typical upper limit of particle size.

SLURRY TRANSPORT TECHNOLOGY

Wasp et al (86) have presented a thorough discussion of the technology of slurry pipeline transportation. They give typical physical properties of commercially transported minerals as shown in Table 19.

In each of these cases, slurry velocities slightly above 5 feet per second (3.4 mph) are adequate to maintain a fairly uniform slurry concentration (concentration ratio greater than 0.8) across the diameter of the pipe thus assuring that the flow is homogeneous. The slurries are therefore nonabrasive at the design velocities allowing use of carbon steel pipe with no interior treatment. These slurries are also restartable; when the pipeline is shut down and the slurry settles it does not plug the line and prevent restarting. From Table 19, it can be seen that the solids' specific gravity is a major factor in determining the maximum particle size and slurry concentration for the homogeneous flow. For a material such as tunnel muck with a specific gravity about 2.6 to 2.7 the maximum particle size is about one-eighth that for coal with a specific gravity about 1.4.

TABLE 19. MINERAL PROPERTIES FOR HOMOGENEOUS SLURRY TRANSPORT

Mineral	Solids Specific Gravity	Maximum Particle (mm)	Ave. Slurry Concentration (% solids by weight)
Coal	1.4	2.4	50
Limestone	2.7	0.3	70
Phosphate	3.2	0.3	65
Copper Concentrate	4.3	0.2	55
Iron Concentrate	4.9	0.14	60

The characteristics of nonabrasiveness, low velocity and power, low cost pipe, and restartability obtained with homogeneous slurries indicate the economic advantages to be gained by forming slurries from fine particles. However, with muck from a mole, which may have lumps up to 10 or 12 inches, a reduction factor of nearly 1,000 would be required to obtain a top particle size of less than .3 mm. At least two, and more likely three, stages of crushing would be required to achieve this reduction factor. Therefore, the major portion of mole muck would need to be processed through one to three large crushers to provide a homogeneous slurry. For slurry transport in the heterogeneous region (concentration ratio less than 0.1) or in the transition region between homogeneous and heterogeneous, the flow conditions, particularly in horizontal pipes, become complicated due to the influence of gravity on the particles. A solids concentration gradient exists across the vertical axis of the pipe. This gradient becomes more severe as the velocity is decreased until a layer of stationary or sliding particles is deposited on the bottom of the pipe. The velocity at which this occurs is called the "deposition velocity." At velocities below the deposition velocity, a bed of solids builds up in the pipe and the friction loss increases with the danger of plugging the pipeline. Thus, it is important to be able to predict the deposition velocity with some accuracy. When particles of mixed sizes make up the slurry, as would be the case for coarse muck, the prediction of the critical deposition velocity becomes quite complicated and unreliable leading to overdesign in an attempt to prevent plugging and other operational difficulties.

STATUS OF SLURRY TRANSPORT

Miscoe (55) recently reviewed the development and status of hydraulic transportation for coal mining. He mentioned that the first commercially operated coal pipeline which operated for 10 years, was built in 1914. This system transported 50 tph of 5-inch top size coal over a distance of 1750 feet through an 8-inch cast iron pipe at a concentration of 50 percent

and a velocity of 4 feet per second. In commenting on long distance overland slurry transport Miscoe states:

> In general, a slurry pipeline becomes more economical than rail haulage when significant lengths of upgraded or new track are required, when cross country route is significantly shorter, or when terrain is too rugged for railroads. Because fine grinding of the transported material is required to achieve low transport velocities with minimum settling and pipeline erosion, preparation and separation costs are very high; up to 40 percent of the capital cost of the pipeline.

In regard to the problems facing slurry transport, Miscoe states:

> The largest problem is the lack of engineering data for the design of systems. Data have been accumulated for both fine and coarse particle transport, but virtually all of it is kept as proprietary information. For large particle transport, the theory is quite complex and little has been accomplished in making design data generally available.
>
> Crushing the solids to fine sizes is undesirable for both mining and tunnel excavation because of the cost for crushing at the origin and for dewatering at the destination. Thus, accurate data for transporting large particles (larger than about 1/8 of the transport pipe diameter) have become increasingly desirable.
>
> Oversizing of pump drives for conservative design is usual but can be very expensive, and lack of knowledge about plugging can make the system risky to operate.
>
> The effects of particle size, high transport concentration, and their interaction are very poorly understood. Most production installations and research work on coal have involved moderate concentration levels of 30 percent by volume or less, and maximum particle sizes of one-fourth of the pipeline diameter or less. This probably is from fear of plugging the pipeline, which cannot be tolerated in production installations and is frustrating in research work. Most existing data indicate that headloss increases as concentration increases up to about 30 percent. Headloss, also increases with particle size, but a large contribution to this headloss is due to the higher transport velocity required to keep the particles in suspension. Above 30 percent, the available data do not show clearly the rate at which headloss increases, but a small amount of evidence indicates that the increase in headloss may level off or even decline under certain conditions.
>
> The worst part of the problem with pumps is that the actual efficiency of performance is known accurately only for water and for some fine particle slurries. No data are available for coarse

particle slurries. Present guesses are that clear water efficiency may be reduced by as much as 70 percent for particle size of 1/3 pipe diameter. Because even a 5 percent improvement at this level would be significant, research is needed.

UNDERGROUND APPLICATION

Because of the volume of solids and water to be handled for application to underground coal mining or tunnel excavation, the separator system must be physically large, and because most separators depend on gravity in the process, the vertical height is likely to be excessive. Also, the finer the particles to be removed, the higher the cost. In the case of tunnel muck, the cost can be justified only on the basis of preventing degradation of the surface environment.

Erosion of the pipe walls can be a serious problem. At present, it is expected that transport of the solids will be by "saltation" or "sliding bed" motion to avoid the excessive wear, attrition, power, and cost associated with high velocity. These two modes of transport cause the pipe wall to wear thin in a period of time. Presently, this is combatted by rotating the pipe until it is uniformly thin and then replacing it. Improved pipe materials and linings are being developed which will reduce erosion problems and costs. Among these are plastic pipes and basalt, urethane, and hardened steel linings.

Leakage or rupture of hydraulic pipelines has more serious consequences underground than in surface systems. Pressure sensors or flow sensors should be attached in strategic locations and set to shut down the pumps and feeders if the line pressure or flow should fall by a preset amount. In the case of hydraulic hoists in deep shafts, safety measures must be given careful consideration because of the high pressures involved, even when the pump is shut down.

Plans for future work are many. A full scale mine haulage system for the Hansa mine in Germany, was planned for operation in late 1977. This would be the largest capacity system built to date. A research facility with 6-, 8-, and 10-inch pipelines, primarily for wear testing and pump development, has been built recently in England. In Essen, West Germany, a pipeline test facility is being built with six pipes ranging from 4 to 14 inches in diameter to pump solids up to 4 inches in size. Tunnel muck as well as coal will be studied because of the belief in the potential advantages of hydraulic transport for tunnel construction. Also, in West Germany, the University of Hanover is planning a large test facility with pipe diameters up to 20 inches. To provide data for the engineering design of hydraulic haulage systems, the Bureau of Mines is constructing the Hydraulic Transport Research Facility for completion in early 1979 at the Pittsburgh Mining and Safety Research Center in Bruceton, Pennsylvania. Six-, 12-, and 18-inch pipeline loops will be used to study run-of-mine coal and other minerals.

Dahl and Petry (15) recently presented an update report on the full scale hydraulic transportation system installed by Consolidation Coal/ Continental Oil to carry coarse coal from the mine face to the preparation plant at its Loveridge Mine near Fairmont, West Virginia. This system,

expected to be in operation in May, 1978, is the result of six years of extensive research and testing. It will service two continuous miners with 8-inch diameter flexible slurry hoses and one long wall section with a 14-inch diameter hose. All three flexible lines terminate in a special design slurry collector-concentrator-feeder. From this point the combined slurry is pumped through a rigid 12-inch steel pipeline about 900 feet vertically to the surface and then 2.4 miles overland to a water separation facility at the preparation plant. Solids are separated and the water clarified for return to the mine. At the mining faces, the system accepts coal in lumps larger than 12 inches, reduces it in a submerged crusher to a maximum size of 4 inches, combines it with water to make a slurry and injects it into the hoses. The flexible-hose sections of the system are mounted on wheels for extension and retraction up to 1,000 feet including following the mining machines around corners.

The major advantage forecast for this system relates to health and safety due to reduced amount of moving equipment, reduced danger of fire and dust explosion, reduced handling of electric cables, and improved control of airborne dust and gas. In addition, a reduction in capital requirement compared to the alternative of conveyors and rail transportation is anticipated.

Haas, et al (31) conducted tests on hydraulic transport of coarse coal at high concentrations in a 4-inch pipeline loop. They concluded that coal with a top particle size of 3/4 inch (18mm) can be successfully pumped in a 4-inch pipeline at volume concentrations up to 25 to 35 percent. At these concentrations coal slurries exhibit behavior characteristics of heterogeneous-type slurries. They feel it is likely that 45 percent is the upper limit for concentration with this size distribution of coal.

INDUSTRY COMMENTS

Comments on slurry transportation heard from industry sources during a series of interviews conducted by Holmes & Narver, Inc. (33) and at the Keystone Workshop (91) include:

a. Shields with bentonite slurry pumped into a sealed bulkhead behind a cutting wheel have been proven feasible. The system moves the muck to the surface in the bentonite suspension after screening out the larger pieces of rock. The system is most adaptable to sands and fine gravel, or sandstone that breaks down into fine components.

b. Pipeline transport has a hard time with large angular or irregular pieces of rock. The wear on the pipeline is a large factor, especially at elbows and fittings. Extending the line is no easy task because the line should be empty first. The muck will settle out of suspension in the line if not continually moving. The volume of the medium required is far greater than the amount of muck to be transported. In order to remove a yard of muck, about 12 yards of material must be handled. A plug in the line or a pump breakdown can shut down the entire operation. Hydraulic pumping requires

large settlement basins or separators at the surface followed by rehandling with a dragline or clam.

c. The need for uniformity of geological conditions may be more important for slurry transport than for alternative methods.

d. Efficient operation of a slurry transport system requires on-line measurement. Instruments for slurry measurements with satisfactory reliability and life in tunnel driving environments are not available.

e. Prior work has been primarily for hoisting in relatively small quantities. You run into problems when you try to increase capacity.

f. Large particles get into problems with the theory. We need a better feel for what goes on in the pump and the pipe, and need to reduce the power required.

g. Greater than 40 percent concentration is required to reduce the amount of water required. We don't know the theory for these higher concentrations.

h. The only time hydraulic pumping of muck from hard rock tunneling was tried (at the Azotea tunnel), it was a miserable failure. Improper planning and design contributed to this failure.

i. The Consolidation Coal slurry system at the Loveridge mine handles about 400 tph of less than 4-inch coal. It is the only commercial underground coal slurry system in the United States. Most slurry pipelines are used for mine or mill tailings disposal.

j. The cost of crushing hard rock for slurry transport will be very large. It costs about 10 dollars per ton (about $175 per tunnel foot in a 20-foot diameter tunnel) to crush muck down to pipeline size.

k. You might be able to pump the muck out but it will cost more than using muck boxes.

l. After many tests of materials in a hydraulic system transporting coal, the wear was found to be less severe than had been anticipated. Reducing particle size in slurry systems reduces wear, but if particle size is too small it creates a dewatering problem.

m. A pipeline system is 70 percent efficient for clear water and 70 percent of that (49%) for a slurry. We have no data for coarse slurry efficiency. Long splinter pieces as found in mole muck can cause plugging in the pipeline.

n. Muck could be pumped if the particle size is small enough, but most of it would need to be ground to finer size. Then the solids

and water need to be separated on the surface. The big problem with hydraulic pumping is getting the fines out of the slurry.

o. Slurry transport of muck has been used successfully when tunneling in St. Peter sandstone, a fine grained, weak, friable material.

CONCLUSIONS

Although slurry transport systems are widely accepted for continuous transport of large volumes of small particle size bulk materials over long distances with relatively steady feed rates, much work remains to be done to develop the engineering data needed for design of systems to transport reliably materials with large and variable particle size under conditions of variable feed rate. Favorable economics of slurry transport under these conditions for short term installations with relatively small volumes and short distance have not been demonstrated. Low cost methods for separation of fines from the slurry, typical of a wide range of rock tunnel muck remain to be developed. Several programs are underway or planned to continue the investigation of slurry transport.

9. PNEUMATIC TRANSPORT SYSTEMS

PRESENT APPLICATIONS

Pneumatic transport of low density materials, such as wood chips and sawdust, and of finely granulated materials such as cement, lime, alumina and other industrial materials has been well established in industry for many years.

The conventional systems, represented by those of the Rader Companies, Inc., and of The Ducon Company Incorporated, blow air through a circular pipeline and feed the material to be transported into the moving airstream. The material feed can be continuous through rotary feeders as in the Ducon pneumatic systems (up to 36 tons per hour) and the Rader pneumatic system (up to 1,300 tons per hour) or intermittent as in Ducon's FLUO/veyor fluid solids pump system (up to 15 tons per hour).

Kennedy Van Saun also makes continuous and intermittent feed systems of conventional design for relatively low capacity conveying of pulverized products. However, the KVS Airfloat systems use a different principle to convey up to 1,300 tons per hour of pulverized material down an incline. In this system, diffused air moving through a porous membrane, in a closed duct or open trough, fluidizes the product, eliminating friction and allowing the material to flow down the conveyor incline by gravity alone.

Some of the earliest pneumatic conveying systems for mining applications were the pneumatic backfill stowing systems built by Markhaus and Co. Ltd. for British and European collieries beginning in the 1930s.

Radmark Engineering, formed by Rader Pneumatics and Markhaus and Co., set out in 1966 to determine the suitability of equipment and methods developed for the wood products industry and backfill stowing to the needs of metal mining and construction activities. One of the first applications tested was backfill stowing at Cominco's Sullivan Mine, Kimberley, British Columbia (69). Although some difficulty was encountered with early equipment, particularly regarding wear in the feeder, the results were encouraging and data obtained was sufficient to permit planning for future filling of stopes. Some observations of interest made by Reynolds (69) as a result of these tests are:

a. The air stream velocity varied with the feed, but had a nominal rate in the order of 90 miles per hour. Particles up to the order of 1-inch size became completely airborne and were relatively motionless within the air stream. Larger particles tended to sink to the bottom of the air stream and move with a rolling action in a narrow track.

b. The system handled slightly more than 100 tons per hour (limited by the feeder).

c. In straight pipe, wear tended to be less in sections prior to the stream reaching peak velocity. Most wear developed over a width of less than 4 inches in the track of the large particles. By rotating the whole blow pipe through six different positions at intervals of 50 hours or 5,000 tons per position it was possible to get a minimum of 50,000 tons wear out of the pipe.

d. The feeder is estimated to be good for something in the order of 100,000 tons between major overhauls.

e. This system is simple in principle and flexible in application. It requires a properly prepared and regulated feed. It is inherently dusty. It is noisy, with levels in the order of 109 dBA at the blower, 103 dBA at the feeder, and 107 dBA at the end of the blow pipe. Commercial silencers are rated capable of reducing the noise level to 85 dBA.

Another backfill stowing system, in operation since 1970, blows desert sand down 1,200 feet and horizontally 200 to 1,200 feet to backfill the Kerr-McGee Nuclear uranium mine at Ambrosia Lake, New Mexico (36). This system transports from 20 to 150 tons per hour of material (all less than 3-inch with 60 percent less than 100 mesh) in a 10-inch oil-well pipe with 6,000 standard cfm of air at an inlet pressure of 6 to 9 psi. Two feeders are used alternately, one in service and one in the shop for rebuilding after each 15,000-20,000 tons of throughput. About 6 man-days are required for rebuilding the feeder. Wear increases for finer material which gets between the rotor tips and the side plates. The clearance between tips and side plates should be kept to a minimum to reduce wear.

The most recent development of low pressure air conveying in the mining industry is in the hoisting of coal and rock from underground mines to the surface. The initial work, based on prior tests conveying tunnel muck about 800 feet laterally and 150 feet vertically at Edmonton, Canada, was performed in 1972 and 1973 in conjunction with Cominco, Ltd. at the Sullivan Mine (77) where tests were carried out to convey waste rock and ore (1/4" - 3" size) a vertical distance of 308 feet at rates up to 40 tons per hour.

During 1973 and 1974 hoisting tests were run on dolomite and coal at the Horden Colliery, South Durham area, England (77). This system had a 50-foot horizontal section at the bottom, a 1,268-foot vertical lift and a 150-foot horizontal section at the top. The dolomite was crushed and screened to 2-inch maximum to simulate waste stone. Two sizes of coal were used (+1/2"-1", and +1"-2"). Both test materials contained some pieces up to 4.5 inches. Washery rejects were tried but could not be handled because the high clay content of this material started to build up in the pipe. Some of the conclusions and recommendations reached are:

a. Two-inch dolomite was successfully conveyed 1,268 feet vertically at rates up to 26.5 tons per hour at air pressures less than 20 psi.

b. Coal was successfully conveyed 1,268 feet vertically at rates up to 50 tons per hour at air pressures less than 25 psi.

c. The floating velocity (the air velocity required to support a particle in the vertical pipe) is a major factor in the design of these systems. Generally, as size and density of a particle increase, the required horsepower per ton per hour per 100 feet of lift increases.

d. The principles and engineering formula developed by Radmark can be used to determine the requirements of hoisting systems with reasonable accuracy.

e. Noise level around the system was reasonable below 18 psi but became uncomfortable at pressures above 18 psi.

f. Screening of materials to positively limit the maximum size of particle is advisable. Material should be produced with the smallest particle size practical and economical in order to minimize the power requirements.

In 1977, another test was run at the Shirebrook Colliery of the National Coal Board in the North Derbyshire area, England (59). This test demonstrated hoisting 1,000 feet vertically in a 12-inch pipe of over 60 tons per hour of run-of-mine coal sized to less than 1 inch with 8,000-10,000 cubic feet per minute of compressed air at 14.5 psi introduced to the system from a 700 hp positive displacement blower. At the end of a 180-foot surface run, the material was discharged to a collection cyclone and taken by belt to the coal preparation plant. This system includes acoustically tuned silencers on the blower, and housing of the blower assembly and controls in separate acoustically sealed chambers. Dust is controlled by water injection.

The acceptance of pneumatic hoisting to provide an alternative means of raising coal to the surface at collieries where the existing hoisting facilities are working at full capacity is illustrated by the interest of the National Coal Board in four additional major coal hoisting systems (66).

In a paper delivered at Pneumotransport IV in June 1978, Powell and Whitfield (65) review applications of pneumatic conveying in the construction industry. These applications include two tunnel projects and ditch backfilling for pipeline projects. Both tunnel projects were located in Canada and demonstrated the potential for pneumatic transport of muck behind a tunnel boring machine in a confined area. It is in the small diameter (less than 12-foot diameter) tunnels where rail switching is difficult or impossible that pneumatic transport offers a potential solution to the problem of muck removal.

The first tests were conducted in tunnels being driven through shales, sandstone, coal seams, preglacial sands and gravels, and glacial till at Edmonton for storm water and sewers. These tunnels were provided with 36-inch diameter boreholes from the surface at 800-foot intervals which were used for hoisting the muck. The blower assembly with an output of 5,800 cfm

at 18 psi powered by a 500 hp electric motor, was housed in an acoustically clad trailer for easy relocation to successive shafts or bore-holes. The Radmark feeder, mounted on skids, was attached to the tunneling machine and had capacity to handle all output from the mole. Both the air supply pipeline and the material transport line were connected to the feeder assembly through telescoping pipe sections, allowing an advance of about 10 feet before having to extend the pipelines. Two major problems became apparent; the negotiation of sharp curves and the increase in size of cuttings from the mole. When in shale, the feeder frequently jammed on pieces larger than 4 inches. A crusher mounted on the skid base and transfer of the equipment from the 7-foot tunnel to a 12-foot tunnel solved these problems. In the 12-foot diameter tunnel, up to 17 tph were transported 800 feet horizontally and 150 feet vertically.

The second application of pneumatic conveying of muck from a tunneling machine in North America was at Halifax, Nova Scotia in 1973-74. The 8-foot diameter tunnel was bored through rock with compressive strength varying from 18,000 to 40,000 psi with advance rates from 2.5 to 10 feet per hour. As in the Edmonton tunnels, the feeder was dragged behind the mole. No crusher was needed due to the small particle size resulting from the hard rock. Two blowers coupled in series were located on the surface. Each blower was driven by a 500 hp motor to provide 6,300 cfm of air at a maximum pressure of 27 psi through a 12-inch air line to the 10-inch material line. The telescoping pipe sections allowed a 16.5-foot advance before having to install additional pipe lengths. The system conveyed about 22 tph horizontally 100 feet and vertically 200 feet. The time for shut down, retracting the telescope, fitting additional lengths of pipe, and coupling up averaged about 12 minutes.

It was concluded from these tests that there appears to be a good application for this type transport system in tunnels of 8 to 14 feet diameter where there is insufficient room for passing track, and that pneumatic hoisting can be used for lifting muck to the surface when rail haulage is used in the tunnel.

Caldwell (8) has pointed out technical problems which are inherent in pneumatic conveying of rock. Included are:

a. Maintaining the velocity of rock particles to insure that they do not settle to the bottom of a horizontal pipeline requires air velocities on the order of 70 to 80 miles per hour.

b. Selection of a small pipe diameter results in high air friction, a high solids loading of the air stream, and a consequent high pressure drop for the system.

c. It is necessary that a large volume of air be gathered in at the blower intake and compressed to the required system pressure. In passing through the pipeline, the air loses pressure thus increasing in volume and velocity. A system operating with a pressure drop of 15 psi undergoes an approximate doubling of air velocity reaching about 150 miles per hour at the exit; a 30 psi system would

reach about 225 miles per hour. (These velocities can be reduced by increasing the diameter of the pipe at points along the pipe length.)

d. Selection of a relatively large pipe diameter lessens the velocity increase (but increases the volume of air required) and, therefore, reduces the abrasive wear of the pipe. Most work to date has involved system pressures around 10 psig.

e. The relatively high velocity of pneumatic conveying, when handling rock, causes extreme abrasion of the conveying pipeline. The degree of wear is influenced by the stone size. A 3-inch size appears to be a reasonable limit. Since a pneumatic system must have a reasonably uniform feed material, it becomes necessary in mining and tunneling to introduce a crusher before the pneumatic system feeder.

f. In vertical pneumatic transport, the minimum air velocity is very much lower than for nonplugging horizontal transport. This results in greatly reduced wear in vertical pipelines. An outstanding example of a system in current operation is one in which 80 tons per hour of coal are being vertically lifted 1,600 feet.

g. At the terminal of the transport system, a receiver hopper or bin must be provided and the transport pipeline must be expanded before entry to reduce the velocity of the stone particles. Surfaces in the receiver subject to stone impingement must be lined with abrasion resistant material. Dust control in the form of a pulse jet bag filter or a scrubber must be provided.

h. The pneumatic conveying of rock requires more power than other methods.

Konchesky, George and Craig (44, 45) performed tests on pneumatic transport of coal using 2-, 4-, 6-, and 8-inch diameter horizontal pipelines and a 50-foot long, 6-inch diameter vertical pipeline. They developed empirical equations for minimum air and power requirements which they propose for use by extrapolation for design of larger and higher capacity systems. For example, assuming a pressure drop of 20 psi and a pickup-to-pipe area ratio of 3 to 1, extrapolation indicates that, at the expense of 1,080 theoretical horsepower, 7,300 actual cubic feet of air per minute (17,200 standard cu ft per minute) would transport through 1,000 feet of 12-inch diameter pipe, 65 tons per hour vertically or 380 tons per hour horizontally of 5-inch maximum coal (sp gr 1.4).

Faddick and Martin (28) made a literature survey to determine the availability and reliability of correlations for estimating pressure drops in pipes and fittings and estimating minimum transport velocities for pneumatic transport of solids. They reported the latest and most extensive reference to be a series of course notes entitled, "The Principles and Practice of Pneumatic Transport," authored by R. A. Duckworth. Faddick and

Martin describe the technique, present the equations and graphs, and give an illustration calculation using the method. They also make the following observations:

a. Tunnel muck, being coarse and heavy, permits only a dilute suspension to develop in pneumatic pipelines.

b. The minimum transport velocity (for the example used) is about 85 mph.

c. It is evident that the high power consumption of a pneumatic pipeline is the result of the high flowrate necessary to keep the solids in suspension.

d. It is apparent that the theory of pneumatic flow of solids is at least as complex as that of slurry flow.

Faddick and Martin (27) in giving the preliminary results of tests conducted on pneumatic transport of rock, made the following observations:

a. A pneumatic pipeline system for tunnel muck conveyance is power intensive and subject to high abrasive wear.

b. The specific power requirements are roughly 4 to 7 kw-hr per ton of solids per 1,000 feet of pipe length.

c. For the muck types tested moisture content is a more important variable than solids size and distribution.

d. Noise levels can range as high as 100 dBA in the vicinity of the muck preparation unit and the blower.

Comments on pneumatic transport heard from industry sources during a series of interviews conducted by Holmes & Narver, Inc. (33) and at the Keystone Workshop (91) include:

a. For the tonnage rates involved in tunneling, you can forget pneumatics.

b. Pneumatic transport has a very high power requirement due to the fact that there is only about 6 percent solids in the air stream. Pneumatic transport is very expensive.

c. Lifting costs could probably be cut 50 percent by using pneumatics.

d. A pneumatic system is a high power user. It requires twice the power of a mechanical system.

e. The feeder will probably be the ultimate factor limiting throughput. At present, the largest feeder is designed for 200 tph; feeders rated at 300 and 400 tph are on the drawing boards. The eventual limits for pneumatic systems with current technology are

probably 300 tph for 300 feet horizontally and 200 tph for 2,000 feet vertically.

f. Moisture content above about 5 percent is very bad for pneumatic systems.

g. The velocity required for lifting is only about 50 percent of that for horizontal transport. Therefore, hoisting should have a low erosion rate even for hard rock.

h. In an urban area, acoustics will be a problem. Covering pumps, motors and muck-air separation equipment with acoustic material will help but not eliminate the problem. A 100 tph system requires a blower with an 800 hp motor which will make a lot of noise.

i. A crusher probably would not be required behind a mole in hard rock.

j. The current problems associated with pneumatic conveying of tunnel muck are: 1) distance limitation, 2) abrasive wear on pipe and feeder, 3) power consumption, 4) capacity limitation, 5) not proven for handling clay and certain other materials.

k. It can be anticipated that high power consumption in a pneumatic conveying system is inherent.

CONCLUSIONS

Pneumatic transport of bulk materials has been demonstrated to be practical and economically competitive for specific applications such as transport of low density or finely divided materials, backfill stowing, and hoisting of coal in special situations. The high velocities required to suspend large, dense particles accelerate pipe wear and cause high power consumption. Transport of large, dense particles in the tonnage range projected for the far term period has not been demonstrated. The problems caused by sticky materials encountered in many tunnel mucks (including rock) have not been investigated.

10. ESTIMATING METHODOLOGY

BACKGROUND

Since 1969, several cost estimating models based on various techniques have been developed for estimating the cost of tunnel construction. Each of these models was developed for a specific purpose; therefore, the methods used, the detail of input data, and the expected accuracy of costs derived vary from model to model. The eight available methodologies were reviewed by Foster, Toporoff, et al., in a report dated January, 1977 (29). Following is a synopsis of their findings.

Techniques presently available are of three general types: Type I employs detailed analysis, Type II uses comparative analysis, and Type III is based on probability analysis.

In Type I estimates, the project cost is developed by definition of the construction method and detailed computation of costs. The construction method to be employed is combined with data on the geometry and geology of the tunnel to derive labor, materials, and equipment quantities and costs from a predetermined data base. Adjustments are then made for a variety of factors, such as regional location of the job, cost escalation, competitive position, and desire to win the job. Finally, costs are added for items such as insurance, contingency, overhead, and profit. This basic technique, represented by the Foster-Miller estimating system, is typically used with variations of detail by tunneling contractors in preparing their competitive bids.

Type II estimates derive a cost of tunnel construction by using historical data from previously constructed tunnels to establish unit costs for the various major construction elements. These costs are then used to prepare curves or equations from which the cost of proposed tunnels can be determined once the geometry and geology are known. This is the most frequently used technique for cost studies. The Harza programs (COHART for hard rock and COSTUN for all types of tunnel construction), the General Research Corporation (GRC) model, the Bechtel method, the unit price technique, and the Singstad, Kehart, November and Hurka (SKNH) method are all examples of this approach. Although the method is perhaps suitable (depending on the details of the specific model) for planning calculations, it is not accepted by contractors for use other than as a quick check on the reasonableness of bid estimates.

Both the Harza programs (COHART and COSTUN) were intended to provide a basis for evaluating the cost effectiveness and usefulness of research programs and new technology. A special feature of the program is that costs are computed from stored cost equations developed from empirical data, field experience, and typical labor crew structures. However, among the costs not computed are mobilization/demobilization costs, power consumption, repairs, and downtime.

The GRC model is a performance and cost simulator for tunneling in rock which might be used by planners and researchers as an aid in analyzing relative cost and performance of existing and proposed tunneling methods. However, the model does not take into account unanticipated breakdowns of equipment or changes in geology. This omission has a considerable effect on advance rate and sizing of material handling equipment.

The Bechtel method is based on the concept of building total costs from basic construction operations. However, the use of averaged bid prices at a given site to establish operation costs is subject to some question, as the average quoted by the three lowest bidders may bear little resemblance to actual costs.

The unit price estimating technique and the SKNH method (which is based on a unit cost per linear foot of a typical rapid transit tunnel) are flexible and simple to use. They have proven acceptable for quick budget estimates when little input data is available, but due to lack of detail and limited accuracy they are unsuitable for comparison of alternative construction methods.

The Type III technique, based on probability analysis, is designed to evaluate the effects of uncertainties in geology and in the performance of men and equipment on construction schedules and costs. The Massachusetts Institute of Technology (MIT) model is a computer based simulation of the tunnel construction process in rock, based on probability analysis. Material handling is not identified as a major component of construction. Little emphasis is placed on detailed cost data, relying instead on major classifications. There is a danger that insight into the significance of the results may be obscured by the large volume of outputs generated.

In conclusion, Foster, Toporoff, et al (29), state that the available cost estimating systems in use have important shortcomings which detract from their accuracy. They therefore combined features from several of the existing techniques to develop a system they believe to be unique.

The Underground Technology Development Corporation (UTDC) system (29) is closely related to the Foster-Miller technique and has a framework for cost development similar to that employed in contractor cost estimates. Job costs are broken down into basic components such as site preparation, dewatering, excavation, lining, etc. A set of conditions (size, shape, length, geology, depth) is prescribed for the tunnel and a construction approach is selected. Methods and equipment to be used with the selected approach are then defined. Labor, equipment, and materials rates and costs are stored in a data bank and combined with the labor, equipment, and materials quantities associated with the methods and equipment selected. Also included in the data bank will be information about the support crews required for initial lining and muck haulage which will match the characteristics of the excavation method selected. Data bank storage will contain some information which changes very slowly with time and other information such as wage rates and equipment costs which change more rapidly. Updated costs can be inserted easily.

The output of the initial calculations is the "base cost" of a tunnel built by the chosen construction method in the prescribed geological environment with average site conditions. This base cost must be corrected by applying factors related to the site, the region, and the time frame of the construction. These corrections are made by inputting identifier information which calls out the appropriate factors from the data bank.

A similar approach (determining a base cost and applying correction factors) is used for each of the basic components of the job. The sum of these corrected base costs gives the total direct cost which is combined with the indirect costs (obtained from the data bank) to obtain the total project cost.

One characteristic of this system of interest to planners and others who may not have strong construction backgrounds is its heavy reliance upon data bank information which can be updated by current construction information.

SELECTION OF ESTIMATING METHOD

The Type III estimating technique, based on probability analysis, is not suitable for the needs of the current study because it was developed for a different purpose, specifically, to evaluate the effects of uncertainties in geology and in the performance of men and equipment on construction schedules and costs.

Although some of the Type II cost models (specifically COSTUN and GRC) would appear to have been intended for evaluation of alternative approaches to such construction functions as material transport, the cost elements and/or cost impacts omitted or overlooked render them questionable regarding accuracy for consideration of all costs and cost impacts for comparison of alternative material transport systems. The other Type II techniques (Bechtel, unit price, and SKNH) appear to be too inaccurate and nonspecific regarding detailed cost elements to be of value for comparison of alternative material transport systems. All of the Type II methods which depend upon historical cost data suffer from the lack of cost records which specifically identify material handling costs and the doubt cast upon the limited data so identified. Also no historical cost data exist for untried material handling systems.

The principal value of the Type I models (Foster-Miller and UTDC) to the evaluation of alternative material handling systems would be the availability of a relevant data bank stored in computer files and a documented computer program for use of the data bank and related cost model. The UTD system (29), in its present form and stage of development, is limited to soft ground tunneling and no documented computer program is available. It was, therefore, not selected for use in the current study.

The cost estimating method selected for this study is a modification of a basic approach frequently used by professional tunneling cost estimators

in preparing competitive bids. The particular model used has been developed by Mr. P. E. (Joe) Sperry* over several years of professional application. This proven estimating technique, which is generally accepted by tunnel contractors, was modified by Mr. Sperry specifically for this study to identify and separate the material handling costs. The routine was then computerized to reduce human error in calculation and to ease the burden of multiple and repetitious estimates.

It is common practice in developing joint venture bids for each major participant in the joint venture to develop an independent project cost estimate. These estimates are then compared with each other (and often with estimates made by independent consultants) in a contractors' joint venture bid comparison meeting. This comparison results in a joint venture agreed project cost which becomes the basis for the joint venture bid. To verify the soundness of the Sperry estimating system, a comparison was made between the estimates obtained by using this system and the joint venture agreed figure for the ten most recent bid estimates prepared with the Sperry system. The contract amount of these ten projects was $697 million. The sum of the ten estimates obtained with the Sperry system was 0.2 percent lower than the sum of the joint venture agreed costs. The average estimate was 0.44 percent higher than the average joint venture agreed cost. The Sperry estimates ranged from 8.5 percent higher than the corresponding joint venture agreed cost to 13.7 percent lower. Three to six independent estimates were included in each bid comparison meeting.

In addition to its proven accuracy, the Sperry method offers the following advantages:

a. Specific jobs are defined in considerable detail including job schedule, work schedules, excavation method and rate, ground support requirements, material handling methods for all materials, time cycles for intermittent operations, and other similar details.

b. Any phase of a job can be included or excluded as desired.

c. Effects on the job schedule and cost of equipment downtime and other delays are included.

d. Most costs are developed from single item prices and rates which are individually indexed to a consistent time frame. (1978 dollars were used.)

e. Cost data can be used in whatever form is available.

f. Material handling costs are separated from other job costs.

g. Costs for alternative material handling systems can be easily introduced.

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*P. E. (Joe) Sperry, Tunnel Consultant, 21318 Las Pilas Road, Woodland Hills, California, 91364.

h. Indirect impacts (reduced or increased ventilation, for example) of alternative material handling systems are included and charged to the material handling system.

i. Base cases using conventional material handling systems for which accurate costs are known are used as a point of departure for estimating costs of alternative material handling systems.

j. The system is easily understood with little training.

k. The system routine was readily computerized.

l. Output sheets generated by the computer are easy to read and manually check.

DESCRIPTION OF ESTIMATING METHOD

The estimating method used for this evaluation of material handling systems consists of six basic steps:

a. Define project

b. Plan project

c. Define work crews and work-day cost

d. Define equipment requirements, including capital and operating costs

e. Determine indirect costs

f. Merge work plan and unit costs to derive job cost.

The data flow for the assembly of job cost and examples of the input work sheets are illustrated in Appendix B.

Project Definition

Specific values for project parameters are selected. These include:

a. Length of tunnel reach and total length of tunnel

b. Access shaft dimensions

c. Excavation method used

d. Excavation production characteristics

e. Initial ground support requirements and quantities of materials

f. Horizontal materials handling method used and equipment required

g. Materials lifting method and equipment

Some of this information is derived from the project plan (schedule, work cycles and project delays caused by equipment downtime), so the first two steps are iterative and must be developed together.

For all projects included in this study, it is assumed that twenty percent of the tunnel will require 270-degree steel sets, twenty percent will require epoxy bolts, and sixty percent will require expansion bolts.

Project Plan

The project plan is derived from the definition of project equipment and the assessment of delays caused by equipment downtime. The plan includes both the work cycles for intermittent material handling equipment and the job schedule, which is determined by:

a. Excavation time and estimates of time required for initial development excavation (drill-and-shoot)

b. Equipment installation and erection

c. Mole relocation

d. Equipment removal

e. Job demobilization and cleanup

The schedule determines the work periods for the various work crews.

The excavation time is determined from the moling time based on an average penetration rate (determined by the assumed geology and state of technology in the time frame of interest) plus time added for delays. The delays considered include:

a. Time for resetting the mole after each penetration

b. Delays caused by bad ground (set placement)

c. Delays caused by material handling system extension

d. Delays caused by ventilation system extension

e. Delays caused by power cable extension

f. Delays caused by shift change

g. Delays caused by mole startup

h. Slowdowns when working on curves

i. Downtime for cutter replacement

j. Downtime for repairs to mole

k. Downtime for repairs to material handling system

l. Downtime for repairs to drills

m. Other miscellaneous downtime

Not included in the project plans for this study are shaft sinking, final concrete lining, and cleanup and moveout following final lining. These were excluded because they are performed independently of the tunnel excavation and remain constant for all projects considered.

Work Crews

The composition of shift work crews (3 shifts per day) is determined for excavation and support, and for materials handling at the heading, at the shaft and on the surface. A crew for removal of the fanline at the end of the job is also determined. Shift wage rates for each labor category are determined from basic hourly rates (Washington, D.C., rates at January, 1978, were used) by correcting for premium hours for shift change, lunch and underground travel, and for rate differentials for work at the shaft or underground. It is assumed that each crew works a full, continuous 8-hour shift. It is necessary to pay premium rates (time and a half) for .5 hour for shift overlap, .5 hour for working through the normal lunch period, and .5 hour for travel to and from the heading.

Daily labor costs per labor category are then determined by multiplying the shift labor rates by the number of shifts per day worked by each category. Summing the daily costs per crew member gives the crew cost per work day.

Equipment Operation and Maintenance

Equipment cost per day of operation is developed on an item-by-item basis for repair labor and for parts and supplies (including power) by applying hourly rates to the hours of operation per day for each equipment item. The daily costs are then summed for the equipment complement for excavation and support and for materials handling.

Development Excavation

The cost for excavation of the initial development area is compiled by defining the basic development area and any auxiliary development area required by the particular material handling systems chosen, by planning the excavation, by defining the work crews and equipment requirements, and by determining daily costs as described in the previous paragraphs. Drill-and-shoot excavation and muck transport by load-haul-dump units are assumed for development excavation.

Saturday Maintenance

The cost of crews for Saturday maintenance is developed for the excavation equipment and for the material handling equipment using the same procedure described for equipment operation and maintenance.

Plant and Equipment

The capital cost and related costs (erection, removal, and freight) of all plant and equipment items are determined on an item-by-item basis. The capital costs charged to the job are derived from the purchase cost by subtracting a salvage value determined from the estimated equipment life in a tunneling environment. Typical equipment life values are shown in Table 20. These values were obtained from the Associated General Contractors' Manual (1) or were estimated by an experienced tunneling engineer.* Purchase costs were obtained for the estimate from manufacturers or by escalating to January, 1978, purchase costs from recent bid preparations.

The major categories of plant and equipment items are:

a. Other than material handling:

Buildings and yard

Utilities

Rock drills

Tunnel and shaft machines

General

b. Material handling:

Utilities

Lifting

Rubber tire vehicles

Rail (or other) haulage system

Tunnel and shaft machines

Indirect Costs

Indirect costs (overhead labor, miscellaneous job expense, insurance and taxes) are calculated using computation sheets illustrated in Appendix B.

*Mr. P. E. (Joe) Sperry, Tunnel Consultant, 21318 Las Pilas Road, Woodland Hills, California, 91364

Compilation of Costs

The job costs are compiled into nonmaterial handling costs and material handling costs for each of the three major cost categories (direct cost, plant and equipment, and indirect costs) and for the total job, by the computerized cost model described in Appendix B.

TABLE 20. PLANT & EQUIPMENT SALVAGE BASIS

Description	Source	Life	
		Equipment (Hours)	Plant (Jobs)
Air Tools	S	-	2
Buildings	S	-	4
Compressors, Electric	A	14,000	-
Compressors, Diesel	A	12,000	-
Conveyors	A	8,000	-
Crane, Crawler	A	15,000	-
Crane, Hydraulic	A	11,000	-
Crushers	A	11,000	-
Drills	A	4,000	-
Electric Equipment	S	-	4
Feeders	A	4,000	-
Hoist, Man	A	12,000	-
Hoist, Muck	A	12,000	-
Hoist, Headframe	S	-	4
Locomotive $\leq$ 15T	A	8,000	-
> 15T	A	10,000	-
Mole	S	8,000	-
Office Equipment, Phones	S	-	2
Pneumatic Blower	A	10,000	-
Pumps, Slurry, Electric	A	5,000	-
Pumps, Water, Electric	A	7,000	-
Rail, Switches	S	-	4
Rail Cars, Muck (Other)	A	12,000	(5)
Screening Plant	A	7,000	-
Stower	S	8,000	-
Surveying Equipment	S	-	5
Ties, Steel	S	-	3
Ties, Wood	S	-	1
Tools	S	-	3
Trailing, Floor	S	6,000	-
Truck, Surface	A	7,000	-
Truck, Underground	S	5,000	-
Utility Pipe & Valves	S	-	2
Vent Fans	A	10,000	-
Lasers & Stands	S	-	2
Vehicles (Autos & Pickups)	S	-	3
Welders	S	-	4

Sources: A = AGC Manual, S = Sperry

11. ESTIMATES FOR CONVENTIONAL SYSTEMS

Although some contractors have tried nonconventional muck transport systems such as pipelines, bucket elevators and belt conveyors, by far the largest number of urban transit tunnels are dug using a dual rail (single track) system for horizontal transport of materials and a crane or hoist for lifting when access to the tunnel is through a shaft. These conventional systems are well established in the tunneling industry. Their designs have evolved over many years of application in tunneling and mining environments.

Project cost estimates were made using conventional material handling systems for the near term and far term cases to serve as a point of departure and basis for comparison when nonconventional material handling systems are introduced as alternatives in the project plan.

PROJECT DESCRIPTION

The tunnel construction projects consist of two parallel tunnels each 10,000 feet long (near term), or each 40,000 feet long (far term). Access to the tunnels is through a service shaft to be used as a ventilation shaft for the completed subway system. The shaft is 30 feet in diameter by 100 feet deep for the near term case and 45 feet in diameter by 200 feet deep in the far term case.

Tunnel excavation in each case is by moling. In the near term case, a 1200-horsepower mole penetrates at an average rate of 2 inches per minute (ipm), 10 feet per hour (fph), with occasional maximum penetrations of 3 ipm (15 fph), producing an average advance rate (production rate) of 118 feet per 24-hour day during the excavation period. In the far term case, a 4000-horsepower mole penetrates at an average rate of 5 ipm (25 fph), with occasional maximum rates of 7 ipm (35 fph), to produce an average advance rate of 313 fpd.

Rock bolts on 4-foot centers and steel sets on 5-foot centers over 270 degrees of the tunnel circumference are used for ground support in various segments of the tunnels. This requires 800 sets in 4000 tunnel feet, 8000 epoxy bolts (8 per row) in 4000 tunnel feet, and 18,000 expansion bolts (16 per row) in 12,000 tunnel feet for the near term case; and four times these quantities for the far term case. In the near term case, pneumatic drills are used for setting rock bolts. Ganged hydraulic drills are assumed for the far term case.

Delays imposed on the mole, both scheduled and unscheduled, reduce the mole availability to 88 percent and the mole utilization to 49 percent of the excavation period for the near term case and to 89 and 52 percent, respectively, for the far term case. These delays are summarized in Table 21. It should be noted that in both the near term and far term cases the tunnel feet total excavated by moling is less than the total project tunnel feet because 560 feet of tunnel are excavated by the drill-and-shoot method during construction of the underground development area. Muck is transported by load-haul-dump (LHD) units during this phase. It is apparent, from the increased penetration rates and reduced delay times

TABLE 21. PROJECT MOLING DELAY TIME

Delay Cause	Description	Near Term (20,000 feet of tunnel)		Far Term (80,000 feet of tunnel)	
		Unit Time	Hours	Unit Time	Hours
Reset Mole	6 ft/stroke	2 min/stroke	108	1 min/stroke	221
Install Rock Bolts			none		none
Install Steel Sets		1 hr/set=30 min delay	400	.33 hr/set=8 min delay	427
Rail Car Derails		.001 hr/tunnel-foot	19	.0005 hr/tunnel-foot	40
Hoisting		.005 hr/tunnel-foot	97	.003 hr/tunnel-foot	238
Install Ventilation		.002 hr/tunnel-foot	39	.001 hr/tunnel-foot	79
Add Power Cable		18 @ 3 hrs	54	78 @ 1 hr	78
Power Outages		1 @ 8 hrs	8	3 @ 8 hr	24
Change Cutters	5% moling time		97		159
Repair Mole	20% moling time		389		636
Repair MH System	5% moling time		97		159
Repair Drills	3% moling time		19		32
Shift Change		.005 hr/tunnel-foot	156	.003 hr/tunnel-foot	256
Startups	17 work days		408		408
Curves		2 work days	48	3 work days	72
TOTAL DELAYS			1997		2924
MOLING TIME		19,440 ft ÷ 10 fph	1944	79,440 ÷ 25 ft/hr	3178
TOTAL EXCAVATION TIME			3941		6102

per unit of tunnel, that significant advances in tunneling technology are assumed for the far term time period.

In both the near term and far term cases, trailing equipment consisting of a balanced floor with car shifter, is used for loading muck in the muck cars from the loading conveyor. The material transport system must be designed to accommodate muck production at the maximum penetration rate to avoid delay of the mole by the material transport system.

In the near term case, 25-ton locomotives (180 hp) pulling six 20-cubic-yard muck cars per train on single-track, 75-pound rails and steel ties are used for horizontal transport. Special flat cars and man-haul cars are provided for incoming materials and personnel. Six switches are used to control the near-shaft traffic and train switching at the heading. Two locomotives and three trains are required. The outbound trains, loaded with 120 loose cubic yards (about 155 tons) of muck, travel at 12.5 miles per hour (1100 feet per minute). Inbound trains, empty except for ground support materials and supplies, travel at 17 miles per hour (1500 fpm). One minute is allowed for switching at the heading and two minutes at the shaft. Four minutes per car (24 minutes per train) are required for muck box dumping. Thus, car filling (23 minutes/train, 6-foot mole advance) and dumping control the haulage cycle for the maximum reach of 10,000 feet. While the mole is regripping, an empty train is spotted at the heading, and the loaded train is pulled onto the mainline track. The loaded train travels to the shaft (9 minutes) and into the unloading station. The empty train travels through the switches (2 minutes) and to the heading (7 minutes) where it has a six minute wait before it can be moved into the loading position. For all reaches less than 10,000 feet as the tunnel is being excavated, the wait period is longer than six minutes. Thus, there will always be one train (without locomotive) at the heading for loading, one train and locomotive at the shaft for unloading and one train and locomotive on haul or waiting. One spare locomotive and two spare muck cars are provided to avoid delay during equipment repair.

For the far term case with its much higher penetration rate and much longer maximum reach, traffic on the rail system could become complex. To keep the number of trains at a manageable level, ten larger cars of 25-cubic-yard capacity are used per train. It also is assumed that the trains operate at 20 miles per hour (1760 fpm) loaded with 325 tons of muck and 27 mph (2400 fpm) empty. To attain these speeds, higher quality trackage and maintenance than are the current common practice will be required. These trains will hold the muck produced by two advance cycles of the mole, requiring 21 minutes of moling at 35 feet per minute. Allowances of 1 minute for switching at the heading, 2 minutes for switching at the shaft, and 4 minutes per pair of cars for dumping (using a balanced hoist) were made. (This will require advances over present technology.) For reaches less than 17,000 feet, one locomotive and train will be required at the shaft for dumping (20 minutes), one locomotive and train on haul, and one train without locomotive at the heading for loading. As the reaches extend beyond 17,000 feet, it will be necessary to add another locomotive and train on haul and a California switch for train passing. The California switch

will be moved ahead as the heading advances until it is at 20,000 feet when the end of the tunnel is reached. Thus, the maximum rail equipment required is two locomotives and trains on haul, one locomotive and train at the shaft, one train at the heading and a California switch, all operating on single-track, 90-pound rail with steel ties. The locomotives are 45-ton (580 hp) for mainline haulage and 30-ton (180 hp) for switching at the shaft. One spare locomotive of each size and two spare muck cars are provided. Six conventional switches are required to meet switching requirements at the shaft and heading.

There is very little train waiting time in the long term transport cycle, and the time allowances and speeds assumed may be difficult to achieve consistently. Therefore, near the end of the reach when moling at the maximum penetration rate, the mole could experience some delay due to the material transport system. Careful synchronization of all rail system operations would be required to avoid such delays.

Muck lifting for the near term case is performed by a 75-ton crane lifting 20-cubic-yard lift-off boxes along guides at 350 feet per minute with a single part line. Four minutes per box are allowed for the hoisting cycle. For the far term case, a 500-horsepower hoist with a headframe, lift-off boxes in balance, guides, a dump scroll and automatic controls is used to unload two muck boxes every four minutes. In both cases, a man-hoist and a 12-ton hydraulic yard crane are provided.

COSTS

Costs are compiled in three major categories (direct cost, plant and equipment, and indirect cost) for each case. Within each category, the costs are separated into materials handling costs and costs other than materials handling. Direct materials handling costs associated with tunnel excavation represent about 35 percent of the total direct costs. The major elements of materials handling direct cost are the subcontract for surface disposal of muck and direct labor costs. The muck disposal contract represents 32 percent of the total direct material handling costs for the near term case and 49 percent for the far term case. Direct labor for material handling is 46 percent (near term) or 28 percent (far term) of the total direct material handling cost.

Direct labor for excavation, ground support, and material handling (the largest element of direct cost) represents 38 percent (near term) and 23 percent (far term) of the total direct costs. This illustrates the increased labor productivity of the far term case. Other direct costs are equipment maintenance and operation expense, supplies, and materials for ground support.

Direct Labor

The direct labor cost is derived by developing 24-hour-day work crews for each major operation and applying a wage rate per shift to the number of man-shifts worked by each labor classification. The cost of direct labor

TABLE 22. DIRECT LABOR CREW COSTS

		Near Term		Far Term	
Labor Classification	Rate per Shift ($/mnsht)*	Man-Shifts	Cost per Day	Man-Shifts	Cost per Day
EXCAVATION AND SUPPORT					
Mole Operator	147/152	3.0	441	3.0	456
Mole Mechanic	142/147	2.7	383	3.7	544
Greaser	122/126	1.0	122	1.0	126
Shifter	135/140	3.0	405	3.0	420
Miners	123/127	6.0	738	12.0	1524
Chucktenders	114/119	3.0	342	6.0	714
Utility Extension	123/127	1.5	185	1.5	191
Compressor Operator	111	3.0	333	-	-
Electrical Foreman	209	1.0	209	1.0	209
Electrician	190	4.0	760	6.0	1140
Bull Gang Labor	107/115	1.0	107	2.0	230
Pumpman	143/148	1.0	143	2,0	296
TOTAL CREW		30.2	4168	41.2	5849
MATERIALS HANDLING					
At Heading					
Extend MH System	114/119	1/5	171	3.0	357
Mechanic	142/147	.3	43	.3	44
Conveyor Operator	139/144	3.0	417	3.0	432
Motorman	139/144	3.0	417	4.8	691
Brakeman	107/115	3.0	321	3.0	345
Bull Gang Foreman	135/140	1.0	135	1.0	140
Bull Gang Labor	107/115	1.0	107	3.0	345

*147/152 = Far Term Rate/Near Term Rate

TABLE 22 (continued)

Labor Classification	Rate per Shift ($/mnsht)*	Near Term Man-Shifts	Near Term Cost per Day	Far Term Man-Shifts	Far Term Cost per Day
At Shaft					
Shaft Mechanic	147	-	-	1.0	147
Motorman	129/144	3.0	387	3.0	144
Brakeman	103/115	3.0	309	3.0	115
Bottomman	114/115	6.0	689	1.0	115
Topman	84	3.0	252	1.0	84
Crane Hoist Operator	117	3.0	351	3.0	351
Oiler	95	3.0	285	3.0	285
On Surface					
Yard Crane Operator	115	1.0	115	1.0	115
Labor Foreman	88	1.0	88	1.0	88
Laborers	84	2.0	168	4.0	336
Truck Feeder Operator	109	-	-	3.0	327
Front End Loader Operator	115	2.0	230	-	-
Truck Driver	75	1.0	75	1.0	75
TOTAL CREW		40.8	4555	43.1	5054
REMOVE FANLINE					
Shifter	135/140	3.0	405	3.0	420
Miner	123/127	6.0	738	6.0	762
Chucktender	114/119	3.0	342	6.0	714
Motorman	139/144	5.1	709	5.1	734

*147/152 = Far Term Rate/Near Term Rate

TABLE 22 (continued)

		Near Term		Far Term	
Labor Classification	Rate per Shift ($/mnsht)*	Man-Shifts	Cost per Day	Man-Shifts	Cost per Day
Brakeman	107/115	3.0	321	3.0	345
Bottomman	114/115	6.0	684	3.0	345
Topman	84	3.0	252	3.0	252
Operator	117	3.0	351	3.0	351
Oiler	95	3.0	285	3.0	285
TOTAL CREW		35.1	4087	35.1	4208
DRILL AND SHOOT (D&S) EXCAVATION					
Shifter	135	3.0	405	3.0	405
Miner	123	12.0	1476	12.0	1476
Chucktender	114	6.0	684	6.0	684
Nipper	123	3.0	369	3.0	369
Heading Mechanic	142	3.0	426	3.0	426
Mucker Operator	147	4.5	662	4.5	662
Powderman	123	3.0	369	3.0	369
TOTAL CREW		34.5	4391	34.5	4391
SHAFT OPERATION DURING D&S EXCAVATION					
Hoist Operator	140	3.0	420	3.0	420
Oiler	113	3.0	339	3.9	339
Topman	106	3.0	318	3.0	318

*147/152 = Far Term Rate/Near Term Rate

TABLE 22 (continued)

		Near Term		Far Term	
Labor Classification	Rate per Shift ($/mnsht)*	Man-Shifts	Cost per Day	Man-Shifts	Cost per Day
Bottomman	114	3.0	342	3.0	342
Loader Operator	115	1.0	115	1.0	115
TOTAL CREW		13.0	1534	13.0	1534
SATURDAY MAINTENANCE					
Excavation					
Mechanic Foreman	140/156	.5	70	.5	78
Mole Operator	147/152	1.0	147	1.0	152
Mole Mechanic	142/147	3.0	426	4.0	588
Greaser	122/126	.5	61	.5	63
Shifter	135/140	1.0	135	1.0	140
Laborer	114/127	3.0	342	4.0	508
TOTAL CREW		9.0	1181	11.0	1529
TOTAL CREW WITH OVERTIME			1772		2294
SATURDAY MAINTENANCE					
Material Handling					
Mechanic Foreman	140/156	.5	70	.5	78

*147/152 = Far Term Rate/Near Term Rate

TABLE 22 (continued)

		Near Term		Far Term	
Labor Classification	Rate per Shift ($/mnsht)*	Man-Shifts	Cost per Day	Man-Shifts	Cost per Day
Mechanic, Trailing Equipment	142/147	2.0	284	3.0	441
Greaser	122/126	.5	61	.5	63
Crane/Hoist Operator	117	1.0	117	1.0	117
Oiler	95	1.0	95	1.0	95
Shaft Mechanic	147	-	-	2.0	294
Topman	84	1.0	84	1.0	84
Bottomman	100/115	1.0	100	1.0	115
Bull Gang Foreman	140	-	-	1.0	140
Laborer	114/115	1.0	114	3.0	345
Motorman	139/144	1.0	139	1.0	144
TOTAL CREW		9.0	1064	15.0	1916
TOTAL CREW WITH OVERTIME			1596		2894

*147/152 = Far Term Rate/Near Term Rate

crews is summarized for the near term and far term cases in Table 22. The direct labor cost is obtained by multiplying the appropriate crew cost per day by the number of days required (obtained from the schedule) to accomplish a specific task. For example, excavation and support (and the associated materials handling) require 164 work days in the near term case but 254 days in the far term case. Moving the mole to the second reach requires 31 days in either case. The material handling system also is moved during this period and the full crew is paid for the entire period for personnel stability, even though the material handling system could probably be moved in less time. There are 33 days of Saturday maintenance in the near term and 51 days in the far term.

Equipment Maintenance and Operation Expense

The direct cost for equipment M&O expense includes maintenance labor and parts and supplies (including power and fuel) for maintenance and operation. (Operating labor is included under direct labor rather than equipment M&O.) The M&O cost per day for each function is derived by determining the hours of operation per day for each piece of equipment used for the function and multiplying by unit rates for repair labor and for parts and supplies. The M&O daily costs are summarized in Table 23 for the near term and far term cases. The project total M&O cost is obtained by multiplying the daily cost of the function by the days required for the function.

Plant and Equipment

The second major cost category, plant and equipment, includes the purchase cost less salvage for each piece of equipment and other capital items, the cost of shipping to the site, erection cost, and cost to remove and ship out. These costs, developed on an item-by-item basis, are summarized in Table 24 by categories. Both the original purchase cost and the total project cost including shipping, installation, and removal are shown.

It can be observed that the capital investment in the material handling system, if new equipment is purchased, is $1.76 million (about 32 percent of total plant and equipment) for the near term case and $4 million (37 percent of total plant and equipment) for the far term. Considering salvage, shipping, installation, and removal, the material handling system capital charges to the project are $646,000 and $1.8 million, respectively.

Indirect Costs

Indirect costs are those expenses which cannot be correlated with specific construction operations and must, therefore, be charged to the job as a whole. These costs include supervisory, engineering, and office labor, and supplies, services, fees, insurance, and taxes. The cost of operation of vehicles assigned to overhead personnel also is included. Insurance and taxes which are directly related to plant and equipment are charged to the material handling and nonmaterial-handling systems as appropriate. Indirect costs are summarized in Table 25 for the near term and far term cases.

TABLE 23. EQUIPMENT MAINTEMANCE AND OPERATION DAILY COSTS

	Near Term			Far Term		
Function/Equipment	Description	Repair Labor ($/Day)	Parts & Supplies ($/Day)	Description	Repair Labor ($/Day)	Parts & Supplies ($/Day)
EXCAVATION AND SUPPORT						
Mole	1,200 hp	111	2,424	4,000 hp	223	7,092
Scrubber	20 hp	6	12	75 hp	9	32
Vent Fan	20,000 cfm	9	102	40,000 cfm	50	571
Rock Bolt Drills	-	11	18	-	47	126
Compressor	1,200 cfm	15	153	300 cfm	6	51
Welding Machine	300 amp	7	46	300 amp	11	68
Impact Wrench	-	5	6	-	10	12
Pump	13 hp	4	14	13 hp	7	29
Pump	30 hp	2	10	30 hp	4	19
TOTAL EXCAVATION AND SUPPORT		169	2,784		366	8,001
MATERIALS HANDLING						
Locomotive, Shaft	-	-	-	30 /180 hp	126	151
Locomotive, Haul	25T/180 hp	300	348	45 /180 hp	324	500
Muck Cars	20 cy	97	65	25 cy	264	168
Flat Cars		1	2		1	2
Man Haul		2	1		2	1
Truck	5 t	20	55	5 t	20	55
Vent Fans	20,000 cfm	9	102	80,000 cfm	101	1,142
Trailing Equipment		0	168		0	353

TABLE 23. (continued)

	Near Term			Far Term		
Function/Equipment	Description	Repair Labor ($/Day)	Parts & Supplies ($/Day)	Description	Repair Labor ($/Day)	Parts & Supplies ($/Day)
Crane/Hoist	75 t	279	266	500 hp	82	334
Yard Crane	12 t	15	24	12 t	30	48
Man Hoist		19	11		19	11
TOTAL MATERIALS HANDLING		742	1,041		969	2,765
BASIC DEVELOPMENT						
Drill, Jumbo	4 drills	90	216	4 drill	90	216
Pump	13 hp	14	58	13 hp	14	58
Pump	30 hp	7	38	30 hp	7	38
Vent Fan	125 hp	10	106	125 hp	10	106
Load-Haul-Dump	5 cy	459	513	5 cy	459	513
Crane	75 t	223	212	75 t	223	212
Front End Loader	6 cy	49	119	6 cy	49	119
TOTAL DEVELOPMENT		852	1,262		852	1,262

TABLE 24. PLANT AND EQUIPMENT COSTS

	Cost (Thousand Dollars)			
	Near Term		Far Term	
Cost Element	Purchase	Total	Purchase	Total
BUILDING AND YARD				
Site Work	-	34	-	34
Offices	38	30	38	30
Shops	23	24	23	24
Storage	11	13	11	13
Miscellaneous	15	9	15	9
TOTAL BUILDINGS AND YARD	87	110	87	110
UTILITIES, EXCAVATION				
Sanitary	-	-	-	11
Water Supply	46	37	178	103
Communications	8	7	17	16
Electrical, Power Company	-	30	-	30
Electrical, Surface	70	66	63	62
Electrical, Underground	178	52	786	209
Ventilation	135	66	668	321
Compressed Air	84	58	22	28
Dewatering	72	41	332	190
Cleaning	2	1	2	1
TOTAL UTILITIES, EXCAVATION	595	367	2,063	971

TABLE 24 (continued)

	Cost (Thousand Dollars)			
	Near Term		Far Term	
Cost Element	Purchase	Total	Purchase	Total
UTILITIES, MATERIALS HANDLING				
Ventilation Fans	50	12	220	92
Starters	13	3	49	12
Fanline	132	75	865	513
Less Excavation System	-135	-66	-668	-319
TOTAL UTILITIES, MATERIALS HANDLING	60	25	465	298
MATERIALS HANDLING, LIFTING				
Man Hoist	43	18	56	26
Foundations	-	-	-	15
Hoist House	-	-	14	12
Head Frame and Bulkhead	-	-	117	58
Muck Hoist	-	-	480	103
Hoist Cable	-	-	8	9
Skip and Scrolls	-	-	102	33
Automatic Controls	-	-	8	8
Guides and Burtons	-	6	71	115
Compartment	-	-	-	6
Buckets	3	1	-	-
Yard Crane	76	11	76	14
Shaft Crane	550	127	-	28
TOTAL MATERIALS HANDLING, LIFTING	672	162	932	427

TABLE 24 (continued)

	Cost (Thousand Dollars)			
	Near Term		Far Term	
Cost Element	Purchase	Total	Purchase	Total
MATERIALS HANDLING, TRANSPORT				
Flat Bed Truck	25	4	25	4
Rail and Switches	128	105	495	314
California Switch	-	-	107	58
Trailing Equipment	325	196	487	329
Diesel Locomotive	285	68	272	64
Diesel Locomotive	-	-	600	136
Muck Cars	240	76	588	165
Flat Cars	30	10	40	13
TOTAL MATERIALS HANDLING, TRANSPORT	1,033	459	2,634	1,084
EXCAVATION AND SUPPORT EQUIPMENT				
Rock Drills and Equipment	22	7	233	118
Mole and Removal Dolly	2,880	903	4,270	1,898
Rock Bolt Platform	25	26	25	26
Scrubber	11	6	31	16
TOTAL EXCAVATION AND SUPPORT EQUIPMENT	2,938	942	4,559	2,058

TABLE 24 (continued)

	Cost (Thousand Dollars)			
	Near Term		Far Term	
Cost Element	Purchase	Total	Purchase	Total
GENERAL EQUIPMENT				
Vehicles	40	13	40	13
Welders	10	3	10	3
Miscellaneous	85	28	85	28
Engineering	11	6	11	6
TOTAL GENERAL EQUIPMENT	175	63	175	63
GRAND TOTAL PLANT AND EQUIPMENT	5,560	32,128	10,915	5,011
MATERIALS HANDLING, PERCENT OF TOTAL	32	30	37	36

TABLE 25. INDIRECT COSTS

Cost Element	Job Cost, Thousand Dollars	
	Near Term	Far Term
OVERHEAD LABOR		
Supervisory	296	406
Engineering	265	353
Office	176	239
Taxes and Insurance	140	190
Move In	28	28
Vehicle Operation	29	37
TOTAL OVERHEAD LABOR	934	1,254
MISCELLANEOUS JOB EXPENSE		
Supplies	60	78
Services	239	395
Fees	10	12
Entertainment, Travel and Miscellaneous	47	47
TOTAL MISCELLANEOUS EXPENSE	356	532
INSURANCE AND TAXES, OTHER THAN MATERIAL HANDLING		
Automotive Insurance	4	6
Builders Risk Insurance	30	87
Contractual Liability Insurance	180	435
Mole Transportation Insurance	27	30
Fidelity Insurance	1	1
Plant and Equipment Insurance	33	56
Medical Insurance	35	48
Plant and Equipment Tax	16	28
Sales Tax	272	604
TOTAL INSURANCE AND TAX, OTHER THAN MATERIAL HANDLING	598	1,295

TABLE 25 (continued)

	Job Cost, Thousand Dollars	
Cost Element	Near Term	Far Term
INSURANCE AND TAXES, MATERIALS HANDLING		
Plant and Equipment Insurance	16	34
Plant and Equipment Tax	8	17
Sales Tax	103	247
TOTAL INSURANCE AND TAX, MH	127	298
GRAND TOTAL, INDIRECT COST	2,015	3,379

COMPUTER COSTING

The cost elements for projects using conventional rail for horizontal transport and crane or hoist for lifting were entered into the computer which compiled a total project cost by the procedure outlined in Appendix B. The cost summaries for the near term and far term cases are presented in Tables 26 and 27. The costs per tunnel foot for the near and far term cases are 504 and 315 dollars per foot, respectively.

MINIMUM MATERIAL HANDLING SYSTEM

When alternative conveyor muck handling systems are substituted for the conventional rail systems, a supplementary intermittent system is required to transport the inflow of equipment, materials, supplies, and personnel and the outflow of personnel, waste and equipment for repair. An estimate, based on the use of a 5-ton supply truck operating in the tunnel, was developed as a minimum cost system to be used in conjunction with a conveyor horizontal transport system for either the near term or far term cases. The estimate for this supplementary system, designated the minimum materials handling system, is summarized in Table 28.

TABLE 26. COST ESTIMATE, RAIL/CRANE, NEAR TERM

BASE CASE NEAR TERM — ESTIMATOR PES — DATE 09/21/77

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	1237228.			994574.		
EQUIPMENT REPAIR LABOR	164386.			197760.		
EQUIPMENT PARTS AND SUPPLIES	538928.			186384.		
SUPPLIES	921258.			79232.		
MATERIAL	898700.			0.		
SUBCONTRACTS	33000.			683338.		
TOTAL DIRECT COST			3793500.			2141288.
PLANT AND EQUIPMENT						
PURCHASE COST	3795300.			1765250.		
SALVAGE	2733285.			1367333.		
NET COST		1062015.			397918.	
RENT	3000.			0.		
FREIGHT IN AND OUT	101000.			122000.		
ERECTION AND REMOVAL	316000.			126000.		
SUBTOTAL OTHER THAN PURCHASE		420000.			248000.	
TOTAL PLANT AND EQUIPMENT			1482015.			645918.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			5275515.			2787205.
INDIRECT COST						
OVERHEAD LABOR	933792.			0.		
MISCELLANEOUS JOB EXPENSE	356500.			0.		
INSURANCE AND TAXES	597609.			126788.		
TOTAL INDIRECT COST			1887901.			126788.
TOTAL		71. PERCENT	7163416.		29. PERCENT	2913993.
TOTAL JOB COST						10077408.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						504.

BASE CASE NEAR TERM — SUMMARY (DOLLARS) — PAGE 1

TABLE 27. COST ESTIMATE, RAIL/HOIST, FAR TERM

BASE CASE FAR TERM — ESTIMATOR PES — DATE 09/21/77

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	2232946.			1580042.		
EQUIPMENT REPAIR LABOR	308230.			429572.		
EQUIPMENT PARTS AND SUPPLIES	2121439.			721596.		
SUPPLIES	2861006.			120096.		
MATERIAL	3594800.			0.		
SUBCONTRACTS	33000.			2776738.		
TOTAL DIRECT COST			11151422.			5628045.
PLANT AND EQUIPMENT						
PURCHASE COST	6884750.			4031900.		
SALVAGE	4256465.			2872588.		
NET COST		2628285.			1159312.	
RENT	3000.			24000.		
FREIGHT IN AND OUT	170000.			311000.		
ERECTION AND REMOVAL	399000.			314000.		
SUBTOTAL OTHER THAN PURCHASE		572000.			649000.	
TOTAL PLANT AND EQUIPMENT			3200285.			1808312.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			14351707.			7436357.
INDIRECT COST						
OVERHEAD LABOR	1253734.			0.		
MISCELLANEOUS JOB EXPENSE	532080.			0.		
INSURANCE AND TAXES	1294409.			298413.		
TOTAL INDIRECT COST			3080223.			298413.
TOTAL		69. PERCENT	17431930.		31. PERCENT	7734770.
TOTAL JOB COST						25166700.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						315.

BASE CASE FAR TERM — SUMMARY (DOLLARS) — PAGE 1

TABLE 28. MINIMUM MATERIALS HANDLING SYSTEM COSTS

Cost Element	Cost				
DIRECT LABOR	Manshifts		$/Shift		$/Day
Drivers, Supply	3	x	$140	=	$420
Yard Crane Operator	1	x	115	=	115
Labor Foreman	1	x	88	=	88
Laborer	1	x	84	=	84
Driver, Flatbed Truck	1	x	75	=	75
TOTAL DIRECT LABOR	7				782

	Dollars/Day	
EQUIPMENT MAINTENANCE AND OPERATION	Repair Labor	Parts & Supplies
Supply Truck, 5 T	84	229
Yard Crane, 10 T	20	32
Man Hoist	19	11
Flatbed Truck	20	55
TOTAL EQUIPMENT M&O	143	327

	Thousand Dollars	
EQUIPMENT COST	Purchase	Job Total
Man Hoist	43	25
Yard Crane	55	23
Flatbed Truck	25	15
Supply Trucks, 2	94	78
TOTAL EQUIPMENT COST	217	141

12. ESTIMATES FOR CONVEYOR SYSTEMS

Many types of conveyors, as described in Sections 6 and 7, have been used successfully for horizontal transport and elevation of bulk materials in mining, construction, and process industry applications. Conveyors are characterized by a continuously moving, looped carrier medium, such as a belt or a chain, adapted to hold and move the bulk material placed on it. The carrier medium is moved by drives placed at either or both ends of the loop, or at intermediate points along the loop. Special adaptors, such as cleats, sidewalls, pockets or buckets, are often attached to the carrier medium to provide load capacity, particularly when the application is for elevating material. The bucket elevator is an example which provides vertical lifting. Long distance (greater than a few hundred feet) horizontal transport of material by conveyor is most practical by some form of belt conveyor. Modifications of belt conveyors have been developed which allow materials to be elevated on very steep grades and even vertically.

Cost estimates were made separately for horizontal transport by conveyor and for lifting of material by several conveyor types.

HORIZONTAL TRANSPORT

System Description

Cost estimates were developed for the base case conditions for both the near term and far term tunneling projects described in Section 2, but with conveyor systems rather than rail systems for the horizontal transport of muck. A crane (near term) or hoist (far term) system is used for vertical lifting of muck, but a belt conveyor or bucket elevator system could be substituted without severe cost impact. Rubber tired vehicles were selected for horizontal transport of men and incoming material. This selection was made upon the realization that installation costs for a light rail system would make overall system costs too high.

The systems are assumed to employ a continuously extended conveyor belt with delays for belt addition only. A single belt bank unit is installed near the shaft. This unit feeds out belt as the tail pulley is pulled along by the mole. Intermediate drives are added as required to provide enough power and to limit belt tension on a belt extending the entire length of the tunnel. The continuous extension capability requires that the system supports be installed without stopping the conveyor operation, so the cost of a special tail pulley assembly which, in concept, provides a protected work space for this function is included in the estimates.

The conveyor support concept is the wire rope mounted type. The conveyor design in the curved section is not defined, but could incorporate any combination of concepts described in Section 6.

Sizing of system power units was accomplished by applying equations cited in references 10 and 32a. In all cases, liberal design allowances were made to cover inefficiencies and off-design characteristics.

This conveyor system concept employs some equipment modifications which have not been fully developed or tested in the capacity or size ranges of interest. To differentiate from current technology systems applied in the same situations, these systems are designated "long term technology."

Estimating Assumptions

It is important to note the qualifying assumptions made relative to operating costs and manning and equipment costs for the conveyor equipment and the assumptions regarding the ability to negotiate curves. In effect, the capital and operating costs of conveyors used in construction projects (although poorly documented, the only data available) are high enough to preclude the use of conveyors in tunneling. Similarly, the use of a segmented conveyor system to negotiate curves would add to the system costs to an extent that would practically preclude the use of conveyors in tunneling projects, particularly where any type of curve is involved.

Thus, the estimates made must ultimately be interpreted by the concerned user. The estimates are probably best interpreted as being optimistically low but representative of those required for conveyor systems which approach competitiveness with rail systems. For example, the equipment costs are representative of (a) conveyors in straight tunnels, or (b) conveyor systems which have solved the problem of negotiating curves without segmenting the systems or adding significantly to the cost of the intermediate equipment in the curved sections. Operating costs include rates which are much higher than those in mining applications of conveyors. Nevertheless, they assume that the using tunnelers are highly familiar with and experienced in the application and use of conveyors. Specifically, the estimates include little allowances for downtime due to belt failures, and a relatively low maintenance rate on drives and other mechanical and electrical components. Another example is that the fineness of the muck is assumed to be controlled, and situations which cause the generation of large, belt-damaging lumps are precluded.

These assumptions are equivalent to saying that for conveyors to be used successfully and competitively they must be used in a proper situation and installed and operated with a degree of skill which is consistent with other industries where conveyors are used.

Equipment Cost Estimates

Belt Costs. Belt costs are directly proportional to the length and width of the belt, once the general type and quality of belt is determined. A basic belt cost was established from a quote for a high quality heavy duty belt produced by a leading supplier. For 30" belt widths, the cost is $14 per foot of belt (or $28/ft conveyor).

Intermediate Equipment. The cost of intermediate equipment was established from an estimate provided by designers of wire rope supported conveyors. Wire rope was added as a separate item. In addition, the use of special

supports to fit the tunnel wall required the addition of a special bracket, which was added as a separate item. Since such a bracket is likely to simplify the normal stands provided with a wire rope system the costs are probably on the high side, making the estimate conservative. Costs on a dollar per running foot of conveyor basis are:

	$/Foot
Idlers, return rollers and support brackets	20
Wire rope	4
Tunnel wall support	4.25

Drives. The conveyor drive unit includes motor, gear boxes or other transmissions, pulleys, frame, and switch gear. It is expected that a tunnel conveyor system would have a hydraulic drive. Suppliers claim that this type of drive is cost competitive with electromechanical systems, so costing should not be affected by this determination. Horsepower is an effective measure of drive costs. Some representative quotes from suppliers are as follows:

hp	$
50	28,000
200	53,000
500	145,000

Other horsepower sizes were estimated from this information.

Belt Bank Units. Cost estimates were obtained from fabricators. The cost per foot of belt stored goes up modestly after the purchase of the basic unit. Cost estimates are as follows:

Storage Capacity (Conveyor Lengh in Feet)	Unit Cost (Dollars)
150	30,000
250	35,000
450	50,000 (projected)
550	55,000 (projected)

Large storage units were used in order to minimize interruptions for adding belt.

Conveyor Units. Conveyor units such as those used to bridge from the mole to the mainline conveyor and from the mainline conveyor to the hoist were estimated from unit length costs obtained from industry. The rule of thumb applied is $6 per foot per inch of width. For a 36-inch width conveyor the cost is $216 per foot of length.

Electrical and Controls. Costs were added to the electrical system for large sized cable, transformers, and expansion of surface installations. A lump sum amount was added for supervisory controls and interlocks.

Other System Components. Other system components were estimated using data from suppliers for similar hardware or an engineering judgment for concepts without precedent.

Labor and Operating Cost Estimates

There are three general categories of costs in this area:

a. System extension crew costs.

b. Assigned crew maintenance costs.

c. Hourly operating costs, including energy, shop maintenance, and parts.

Because of the lack of historical data and the conceptual nature of the system, there is a significant degree of judgment associated with estimates in each area. The maintenance performed by the assigned crew must be carefully weighed against maintenance costs included in the hourly operating costs. Hourly operating cost data are believed to include both costs; to include these costs in duplicate could distort the entire estimate.

Extension Crews. The near term case includes 1/2 man for extension. One idler support assembly, and four idlers would be installed every two hours. If necessary, the man would be aided by the mechanic.

The far term case requires that an idler support and idlers be installed every forty minutes. Accordingly, the extension crew is expanded to 1 1/2 men, supported by bull gang and mechanic labor as required. An electrician is also available for one shift.

Assigned Mechanics. The near term case assigns one mechanic full time, and bull gang labor half time. The far term case expands this crew to 1 1/2 mechanics and a full-time bull gang laborer.

Hourly Operating Costs. The cost estimates include the following hourly operating costs for combined conveyor units.

	Repair Labor		Parts & Supplies	
	$/Hr	$/Day (12 Hrs)	$/Hr	$/Day (12 hrs)
Near Term	30	360	40	480
Far Term	60	720	80	960

The labor costs can be readily translated back into crew size to gauge the labor intensity of these overall operations. The far term case assumes a more optimistic level of conveyor performance in keeping with improved design, operation and knowledge of use over a period of developments.

Other Cost Impacts

The conveyor system must be highly available and cannot contribute significantly to delays in the overall excavation process. Any delays extend direct cost almost proportionally to time delay. On a cost-per-day-of-delay basis, this amounts to $14,000 per day in the near term case and $23,000 per day in the far term case.

There are two primary factors contributing to delay: (a) unexpected downtime, or unavailability, and (b) delays due to predictable action, such as belt addition in the case of conveyors. An estimated 5% downtime is included to cover the unexpected.

In the near term case, rather than stand the added cost associated with delays for belt additions, a large belt bank was used so that belt addition could usually be made on Saturdays. Under these assumptions, delays attributed to the conveyor systems are equivalent to the delays associated with the rail system. For the far term case, advance rates of over 300 feet per day create the necessity for adding belt every few days. The activity associated with adding belt is assumed to take two hours. Without taking advantage of scheduling, this could cause delays of 320 hours, or 13 days (2 hrs x 160 extensions). The estimate was made based on scheduling belt extensions concurrent with mole cutter changes, and taking advantage of Saturdays for extensions when possible. This results in an added 6-day delay, compared with rail, for the far term conveyor case.

Computer Costing

The data elements and assembly procedure for costing a tunnel construction project by use of the computer program are summarized in Appendix B. The major cost elements developed by the methods indicated and other cost data were entered into the computer, which produced the cost summaries for the near term and far term cases presented in Tables 29 and 30.

The costs per tunnel foot for the near and far term horizontal conveyor cases are $502 and $318 per tunnel foot, respectively.

CONVEYORS FOR LIFTING

Systems Description

Cost estimates were developed for projects employing five conveyor system types suitable for lifting muck as alternatives for the crane or hoist used for this function in the base cases. The material handling system concepts were developed by substituting one of the conveyor types for the crane used for muck elevating in the near term case, and for the hoist used for this function in the far term case. In each case the conveyor lift system receives muck at the same point in the tunnel and deposits it in the same hopper (located on the surface) as that used for the base case crane or hoist, which gives a direct comparison of the lifting alternatives.

TABLE 29. COST ESTIMATE, CONVEYOR-CRANE, NEAR TERM

NT CONV HOIST LT T-RTV IN MH   ESTIMATOR HVS   DATE 09/26/77

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	1230143.			724727.		
EQUIPMENT REPAIR LABOR	164386.			203229.		
EQUIPMENT PARTS AND SUPPLIES	538928.			200061.		
SUPPLIES	920125.			66013.		
MATERIAL	898700.			0.		
SUBCONTRACTS	33000.			683338.		
TOTAL DIRECT COST			3785281.			1877369.
PLANT AND EQUIPMENT						
PURCHASE COST	3795300.			2032340.		
SALVAGE	2733285.			1436451.		
NET COST		1062015.			595889.	
RENT	3000.			0.		
FREIGHT IN AND OUT	101000.			176000.		
ERECTION AND REMOVAL	316000.			100000.		
SUBTOTAL OTHER THAN PURCHASE		420000.			276000.	
TOTAL PLANT AND EQUIPMENT			1482015.			871889.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			5267296.			2749258.
INDIRECT COST						
OVERHEAD LABOR	933792.			0.		
MISCELLANEOUS JOB EXPENSE	356500.			0.		
INSURANCE AND TAXES	597552.			141637.		
TOTAL INDIRECT COST			1887844.			141637.
TOTAL		71. PERCENT	7155140.		29. PERCENT	2890895.
TOTAL JOB COST						10046034.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						502.

PAGE 1

TABLE 30. COST ESTIMATE, CONVEYOR-HOIST, FAR TERM

LT CONVEYOR HOIST LT TECH — ESTIMATOR HVS — DATE 12/30/77

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	2270149.			1686434.		
EQUIPMENT REPAIR LABOR	313694.			422430.		
EQUIPMENT PARTS AND SUPPLIES	2169776.			525146.		
SUPPLIES	2867833.			125059.		
MATERIAL	3594800.			0.		
SUBCONTRACTS	33000.			2776738.		
TOTAL DIRECT COST			11249251.			5535807.
PLANT AND EQUIPMENT						
PURCHASE COST	6884750.			4561920.		
SALVAGE	4256465.			3133708.		
NET COST		2628285.			1428212.	
RENT	3000.			24000.		
FREIGHT IN AND OUT	170000.			352000.		
ERECTION AND REMOVAL	399000.			269000.		
SUBTOTAL OTHER THAN PURCHASE		572000.			645000.	
TOTAL PLANT AND EQUIPMENT			3200285.			2073212.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			14449536.			7609018.
INDIRECT COST						
OVERHEAD LABOR	1253734.			0.		
MISCELLANEOUS JOB EXPENSE	532080.			0.		
INSURANCE AND TAXES	1297167.			320073.		
TOTAL INDIRECT COST			3082981.			320073.
TOTAL		69. PERCENT	17532517.		31. PERCENT	7929092.
TOTAL JOB COST						25461609.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						318.

LT CONVEYOR HOIST LT TECH — SUMMARY (DOLLARS) — PAGE 1

A crane is included in each concept to provide for vertical transport of equipment, incoming materials and oversize muck. Horizontal transport of muck and materials is by rail systems identical to those in the near term and far term base cases.

The alternative conveyor lift systems used are:

a. Inclined belt conveyor

b. Steep conveyor (Flexowall)

c. Spiral conveyor (Serpentix)

d. Covered belt conveyor (Beltavator)

e. Bucket elevator

The trade names given for the non-conventional systems are to help identify the concept. These conveyor types are described in Section 7. A variation of the covered belt conveyor, known as the Loop Belt, was not included because the manufacturer considered it to be non-competitive with the Beltavator at the relatively low tonnage rates and conditions of the projects defined.

All the conveyor systems, including the bucket elevator, require a rail car dump system, a means of screening to remove oversize lumps, and provisions for converting the intermittent delivery of muck from the rail cars to the continuous and uniform feed required by the conveyors. The costs of this equipment are included in the estimates. The estimates assume that only a very small portion of the muck produced by the mole is too large to be handled by the conveyors and that the major portion can be handled by any of the conveyor types or the bucket elevator without crushing.

The following costs are affected by the substitution of alternative lift systems for muck removal:

a. Development excavation

b. Operating crew for lift system

c. Operating cost

d. Equipment cost

e. Equipment installation, dismantling and freight

f. Scheduled excavation days (if availability varies)

<u>Starting Chamber</u>

The development excavation size and details of the configuration may need to be changed to accommodate each of the conveyor lift systems. In

some cases, an auxiliary shaft may be required. The impact on the development excavation area must be considered separately for each concept, but all concepts require excavation of a pit for the rail car dump and muck screening operations. This is estimated to be a pit of 3x3x4 yards or 36 cubic yards of excavation.

Inclined Conveyor. The inclined conveyor using a conventional belt requires an auxiliary slant shaft, which normally is not part of the final tunnel system, although it could be used for many purposes such as ventilation or access. A shaft at least 8x8 feet is required for maintenance access. The length of the shaft depends on the angle of slope and the depth of the tunnel. The permissible angle depends on the muck properties. The maximum angle is normally 18 degrees. For costing purposes, a conservative angle of 15 degrees was used. Hence, the length of the sloped shaft is about four times the depth from the tunnel invert to the surface.

It is assumed that no excavated pit is required to support the inclined conveyor system. The slant shaft lengths and excavated volumes used for costing purposes are:

a. 100-foot tunnel depth (near term)
400 feet, 1,000 cubic yards.

b. 200-foot tunnel depth (far term)
800 feet, 2,000 cubic yards.

Depending on project circumstances, this shaft may be useful for access purposes, or backfilled at the end of the project. It is assumed to be backfilled in the estimate.

Steep Conveyor. Conveyor systems such as the Flexowall that use a special belt can be used at angles up to 70 degrees. As the slope increases, the carrying capacity of the belt (for given width) decreases so there is a tradeoff between slope angle and other factors. A 45 degree slope is conservative for an uncovered belt. This reduces the length of a sloped shaft to 1.4 times the tunnel depth. The use of a separate slant shaft leaves the entire service shaft open for general support. No pit is required to feed this type system.

For costing purposes, an 8x8-foot sloped shaft is assumed, resulting in the following lengths and excavation volumes:

a. 100-foot tunnel depth (near term)
141 feet, 333 cubic yards.

b. 200-foot tunnel depth (far term)
282 feet, 666 cubic yards.

Spiral Conveyor. The availability of conveyors that can turn tight horizontal curves opens the possibility of using a spiral conveyor to lift muck through a shaft. If the conveyor spirals up the wall of the service shaft, the shaft would require enlargement to 35 feet in diameter (5 feet larger than normal for the near term case) to avoid excessive reduction of shaft space. This would add approximately 75 cubic yards to the excavation for

the near term case, but none to the long term case, which assumes that a larger shaft is available for the transit system.

Covered Belt Conveyor. Systems that use two synchronized parallel conventional belts to form a pocket for vertical transport of material have been demonstrated. These systems have the potential for use in conventional shafts without additional shaft or pit excavation.

Bucket Elevator. The bucket elevator has been demonstrated for muck lifting in a conventional service shaft with minimum disruption of the shaft space for other uses. The bucket elevator installation has a pit below the normal service tunnel floor for gravity filling of the buckets. Therefore, in addition to the 36-cubic-yard excavation required for rail car dumping, the bucket elevator has an excavation 10 yards deep by 2 yards wide by 3 yards long, or 60 cubic yards, for elevator filling.

Operating Crews

The crane and hoist systems used in the basic rail/hoist concepts require the following manning totals for three-shift operation.

	Crane (400 tph)	Hoist (900 tph)
Bottom Man	6	1
Top Man	3	1
Operator	3	3
Oiler	3	3

The crane system requires more top and bottom men because it lifts muck boxes from the rail trucks and dumps them at the surface. This requires two bottom men per shift to attach the lifting device to the muck boxes and one top man per shift to assist the operator with dumping. The hoist either engages the muck boxes automatically or receives the muck directly from an automatic rail car dump and dumps automatically by means of a skip guideway. Thus, the hoist top man and bottom man are used for one shift only to handle incoming materials. The oiler is required on each shift by work rules.

When continuous conveyor systems are introduced for muck lifting, a crane is still required for handling incoming materials and equipment transport during one shift per day. This requires the basic crane crew, consisting of crane operator, top man, bottom man, and oiler. In addition, an operator is provided on each shift to monitor the muck lift system, and a bull gang laborer is provided on one shift for daily muck cleanup around transfer points. Thus, the total crew for materials and muck lifting operations is:

	All Systems (400 and 900 tph)
Crane Operator	1
Bottom Man	1
Top Man	1
Oiler	1
Conveyor Operator	3
Bull Gang Laborer	1

This crew is the same size as for the 900 tph hoist system, but in most cases the work load per man will be very light, which offers the possibility of crew reduction by careful work scheduling, if work rules do not interfere.

Operating Costs

Operating costs are not well known for new systems and are often difficult to estimate with accuracy. However, some costs such as electrical energy costs, can be reliably calculated.

Energy. For the lift systems operating at reasonable efficiencies energy costs are calculated as follows:

	Peak Tonnage (ton/hr)	Average Tonnage (ton/hr)	Lift Height (ft)	hp	Energy Cost ($.06 kw hr) ($/hr)
Near Term	400	250	160	41	$ 2.46
Long Term	900	640	260	168	$10.08

Assumptions for calculations:

a. Maximum tonnage rate is used; this is conservative because most motors draw power proportional to work expended.

b. Uses 1 kw per hp to allow for inefficiencies; results in a .74 efficiency factor.

c. Energy costs multiplied by mole time (hours/day) for daily costs.

Lubrication. Lubrication costs are fairly insignificant for conveyor systems with sealed bearings. The estimates include $.60/hr (near term) and $2.00/hr (long term) for this purpose.

Repair Labor. The following repair labor costs are used in the estimates. They are based on a comparison of the relative complexity of the equipment with known systems.

	Cost/Operating Hour	
	Near Term	Long Term
Inclined Belt Conveyor	$2.00	$ 4.00
Steep Conveyor Belt	2.00	4.00
Spiral Conveyor	5.00	10.00
Covered Belt Conveyor	4.00	8.00
Bucket Elevator	4.00	8.00

Repair Parts. The estimates assume that parts costs for a project are 10 percent of the equipment purchase price. The following repair parts costs are based on the plant and equipment costs developed in the next section.

	Dollars/Hour	
	Near Term	Far Term
Inclined Belt Conveyor	6.15	10.91
Steep Conveyor	6.16	16.81
Spiral Conveyor	19.09	22.82
Covered Belt Conveyor	6.16	22.82
Bucket Elevator	6.16	20.62

Plant and Equipment Cost

The plant and equipment costs are based on information from suppliers. The reliability of the costs used varies from system to system. In all cases, the costs should be considered as "ball park", without the benefit of bid competition and refined engineering.

Bucket Elevator

The costs for car dump, and screen and feed units are included in all the estimates to account for the transfer of muck between the intermittent rail haul system and the continuous lifting system. The source is a quote from a supplier.

	Thousand Dollars		
	Basic Elevator	Car Dump	Screen & Feed
Near Term (400 tph)	165	100	55
Far Term (900 tph)	360	139	150

Inclined Conveyor. The inclined conveyor system rises to the surface through a 25 percent slope, inclined shaft and extends above the surface at the same slope to reach a height of 60 feet at the top of the receiving

hopper. The following equipment cost estimates include the subsurface and above surface (including supporting structure) portions of the system. These estimates can be compared to an estimate of $300 per foot for an inclined conveyor installed recently on a tunneling job.

Near Term Case

Intermediate Equipment, subsurface $100/ft x 400 ft	=	40,000
Intermediate Equipment, above surface $216/ft x 240 ft	=	51,840
Drives - Two 50 hp @ $14,000	=	28,00
		119,840
Total (640 ft)		$178.25/ft

Far Term Case

Intermediate Equipment, subsurface $120/ft x 800 ft	=	96,000
Intermediate Equipment, above surface $252/ft x 240 ft	=	60,480
Drives - Two 150 hp @ 58,000	=	116,000
		272,480
Total (1,040 ft)		$262/ft

Steep Conveyor. Belt costs are much higher for this system than for a conventional conveyor. The system, however, is much shorter because of its steeper angle. The near term case length is 225 feet and the far term case length is 366 feet, including the 60-foot elevation above the surface.

System costs are estimated to be:

Near Term

Belt: 2 x 225 x $130/ft	58,500
Other Intermediate Equipment $100/ft	22,500
Drive - One 70 hp (special)	40,000
	$121,000

Far Term

Belt: 2 x 366 x $428/ft	313,297
Other Intermediate Equipment $100/ft	36,600
Drive - One 350 hp (special)	70,000
	$419,896

Spiral Conveyor. The source is an engineering estimate from the manufacturer.

Near term case	$315,000
Far term case	510,000

Covered Belt Conveyor. The source is an engineering estimate from the manufacturer.

Near term case	$127,000
Far term case	200,000

Availability Factor

Muck hoisting by crane or hoist is estimated to contribute delay time of about .005 hours per tunnel foot (about 5% of the mole time) to the total delay time of the mole. It is anticipated that properly operating, continuous lift systems would cause slightly less delay time.

The following arbitrary predictions of unavailability were used for estimating the costs of the conveyor systems:

	Unavailability
Inclined Belt Conveyor	3%
Steep Conveyors	4%
Spiral Conveyor	4%
Covered Belt Conveyor	4%
Bucket Elevators	4%

Since the differences between these unavailabilities and the 5% baseline system cause only small cost savings, they do not play a significant role in the cost evaluation, although each day of delay adds $14,000 (near term) or $23,000 (far term) to the cost of the project.

Computer Costing

The data elements and assembly procedure for costing a tunnel construction job by use of the computer program are summarized in Appendix B. The major cost elements developed by the methods indicated and other cost data were entered into the computer, which produced the cost summaries for the near term and far term cases presented in Tables 32 through 41.

The costs per tunnel foot for the near term and far term conveyor lifting cases are summarized in Table 31.

TABLE 31. PROJECT COSTS WITH CONVEYOR LIFTING

	DOLLARS PER TUNNEL FOOT	
CONVEYOR TYPE	Near Term	Far Term
Inclined Belt Conveyor	504	316
Steel Conveyor	500	317
Spiral Conveyor	505	317
Covered Belt Conveyor	498	314
Bucket Elevator	502	314

TABLE 32. COST ESTIMATE, RAIL/INCLINED CONVEYOR, NEAR TERM

NEAR TERM RAIL CONVEYOR — ESTIMATOR HVS — DATE 09/22/77

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	1228392.			922652.		
EQUIPMENT REPAIR LABOR	163792.			177164.		
EQUIPMENT PARTS AND SUPPLIES	533248.			172766.		
SUPPLIES	919749.			102068.		
MATERIAL	898700.			0.		
SUBCONTRACTS	33000.			690446.		
TOTAL DIRECT COST			3776882.			2065095.
PLANT AND EQUIPMENT						
PURCHASE COST	3795300.			1586090.		
SALVAGE	2733285.			1183117.		
NET COST		1062015.			402973.	
RENT	3000.			24000.		
FREIGHT IN AND OUT	101000.			144000.		
ERECTION AND REMOVAL	316000.			176000.		
SUBTOTAL OTHER THAN PURCHASE		420000.			344000.	
TOTAL PLANT AND EQUIPMENT			1482015.			746973.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			5258897.			2812068.
INDIRECT COST						
OVERHEAD LABOR	933792.			0.		
MISCELLANEOUS JOB EXPENSE	356500.			0.		
INSURANCE AND TAXES	597249.			115865.		
TOTAL INDIRECT COST			1887541.			115865.
TOTAL		71. PERCENT	7146438.		29. PERCENT	2927933.
TOTAL JOB COST						10074371.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						504.

TABLE 33. COST ESTIMATE, RAIL/STEEP CONVEYOR, NEAR TERM

NEAR TERM RAIL/STEEP CONV　　ESTIMATOR HVS　　DATE 09/21/77

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	1228392.			889707.		
EQUIPMENT REPAIR LABOR	163792.			172423.		
EQUIPMENT PARTS AND SUPPLIES	533248.			166145.		
SUPPLIES	919749.			88022.		
MATERIAL	898700.			0.		
SUBCONTRACTS	33000.			687298.		
TOTAL DIRECT COST			3776882.			2003595.
PLANT AND EQUIPMENT						
PURCHASE COST	3795300.			1587250.		
SALVAGE	2733285.			1183883.		
NET COST		1062015.			403368.	
RENT	3000.			24000.		
FREIGHT IN AND OUT	101000.			143000.		
ERECTION AND REMOVAL	316000.			174000.		
SUBTOTAL OTHER THAN PURCHASE		420000.			341000.	
TOTAL PLANT AND EQUIPMENT			1482015.			744368.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			5258897.			2747962.
INDIRECT COST						
OVERHEAD LABOR	933792.			0.		
MISCELLANEOUS JOB EXPENSE	356500.			0.		
INSURANCE AND TAXES	597249.			114854.		
TOTAL INDIRECT COST			1887541.			114854.
TOTAL		71. PERCENT	7146438.		29. PERCENT	2862817.
TOTAL JOB COST						10009255.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						500.

NEAR TERM RAIL/STEEP CONV　　SUMMARY (DOLLARS)　　PAGE 1

TABLE 34. COST ESTIMATE, RAIL/SPIRAL CONVEYOR, NEAR TERM

NEAR TERM RAIL SPIRAL CONV — ESTIMATOR HVS — DATE 09/22/77

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	1228392.			855167.		
EQUIPMENT REPAIR LABOR	163792.			173636.		
EQUIPMENT PARTS AND SUPPLIES	533248.			178819.		
SUPPLIES	919749.			73606.		
MATERIAL	898700.			0.		
SUBCONTRACTS	33000.			683998.		
TOTAL DIRECT COST			3776882.			1965225.
PLANT AND EQUIPMENT						
PURCHASE COST	3795300.			1841250.		
SALVAGE	2733285.			1351523.		
NET COST		1062015.			489728.	
RENT	3000.			24000.		
FREIGHT IN AND OUT	101000.			145000.		
ERECTION AND REMOVAL	316000.			192000.		
SUBTOTAL OTHER THAN PURCHASE		420000.			361000.	
TOTAL PLANT AND EQUIPMENT			1482015.			850728.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			5258897.			2815952.
INDIRECT COST						
OVERHEAD LABOR	933792.			0.		
MISCELLANEOUS JOB EXPENSE	356500.			0.		
INSURANCE AND TAXES	597249.			130880.		
TOTAL INDIRECT COST			1887541.			130880.
TOTAL		71. PERCENT	7146438.		29. PERCENT	2946832.
TOTAL JOB COST						10093270.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						505.

NEAR TERM RAIL SPIRAL CONV — SUMMARY (DOLLARS) — PAGE 1

TABLE 35. COST ESTIMATE, RAIL/COVERED BELT, NEAR TERM

NT RAIL/COVERED BELT, PINCH | ESTIMATOR HVS | DATE 09/21/77

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	1228392.			850916.		
EQUIPMENT REPAIR LABOR	163792.			170964.		
EQUIPMENT PARTS AND SUPPLIES	533248.			160294.		
SUPPLIES	919749.			71690.		
MATERIAL	898700.			0.		
SUBCONTRACTS	33000.			683592.		
TOTAL DIRECT COST			3776882.			1937455.
PLANT AND EQUIPMENT						
PURCHASE COST	3795300.			1592250.		
SALVAGE	2733285.			1187183.		
NET COST		1062015.			405068.	
RENT	3000.			24000.		
FREIGHT IN AND OUT	101000.			145000.		
ERECTION AND REMOVAL	316000.			184000.		
SUBTOTAL OTHER THAN PURCHASE		420000.			353000.	
TOTAL PLANT AND EQUIPMENT			1482015.			758068.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			5258897.			2695522.
INDIRECT COST						
OVERHEAD LABOR	933792.			0.		
MISCELLANEOUS JOB EXPENSE	356500.			0.		
INSURANCE AND TAXES	597249.			114157.		
TOTAL INDIRECT COST			1887541.			114157.
TOTAL		72. PERCENT	7146438.		28. PERCENT	2809680.
TOTAL JOB COST						9956118.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						498.

TABLE 36. COST ESTIMATE, RAIL/BUCKET ELEVATOR, NEAR TERM

NEAR TERM RAIL/BUCKET EL. ESTIMATOR HVS DATE 09/21/77

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	1228392.			856230.		
EQUIPMENT REPAIR LABOR	163792.			204698.		
EQUIPMENT PARTS AND SUPPLIES	533248.			180801.		
SUPPLIES	919749.			75604.		
MATERIAL	898700.			0.		
SUBCONTRACTS	33000.			684099.		
TOTAL DIRECT COST			3776882.			2001435.
PLANT AND EQUIPMENT						
PURCHASE COST	3795300.			1631250.		
SALVAGE	2733285.			1212923.		
NET COST		1062015.			418328.	
RENT	3000.			24000.		
FREIGHT IN AND OUT	101000.			145000.		
ERECTION AND REMOVAL	316000.			184000.		
SUBTOTAL OTHER THAN PURCHASE		420000.			353000.	
TOTAL PLANT AND EQUIPMENT			1482015.			771328.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			5258897.			2772760.
INDIRECT COST						
OVERHEAD LABOR	933792.			0.		
MISCELLANEOUS JOB EXPENSE	356500.			0.		
INSURANCE AND TAXES	597249.			117764.		
TOTAL INDIRECT COST			1887541.			117764.
TOTAL		71. PERCENT	7146438.		29. PERCENT	2890525.
TOTAL JOB COST						10036962.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						502.

NEAR TERM RAIL/BUCKET EL. SUMMARY (DOLLARS) PAGE 1

TABLE 37. COST ESTIMATE, RAIL/INCLINED CONVEYOR, FAR TERM

LT RAIL/CONVEYOR ESTIMATOR HVS DATE 09/23/77

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	2201945.			1709250.		
EQUIPMENT REPAIR LABOR	303271.			465520.		
EQUIPMENT PARTS AND SUPPLIES	2081159.			734882.		
SUPPLIES	2855253.			177392.		
MATERIAL	3594800.			0.		
SUBCONTRACTS	33000.			2789430.		
TOTAL DIRECT COST			11069428.			5876479.
PLANT AND EQUIPMENT						
PURCHASE COST	6884750.			3897900.		
SALVAGE	4256465.			2766646.		
NET COST		2628285.			1131254.	
RENT	3000.			24000.		
FREIGHT IN AND OUT	170000.			347000.		
ERECTION AND REMOVAL	399000.			263000.		
SUBTOTAL OTHER THAN PURCHASE		572000.			634000.	
TOTAL PLANT AND EQUIPMENT			3200285.			1765254.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			14269713.			7641729.
INDIRECT COST						
OVERHEAD LABOR	1253734.			0.		
MISCELLANEOUS JOB EXPENSE	532080.			0.		
INSURANCE AND TAXES	1292107.			292943.		
TOTAL INDIRECT COST			3077921.			292943.
TOTAL		69. PERCENT	17347634.		31. PERCENT	7934672.
TOTAL JOB COST						25282306.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						316.

LT RAIL/CONVEYOR SUMMARY (DOLLARS) PAGE 1

TABLE 38. COST ESTIMATE, RAIL/STEEP CONVEYOR, FAR TERM

LONG TERM STEEP CONVEYOR — ESTIMATOR HVS — DATE 09/22/77

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	2232946.			1686502.		
EQUIPMENT REPAIR LABOR	308230.			467064.		
EQUIPMENT PARTS AND SUPPLIES	2121439.			769268.		
SUPPLIES	2861006.			157894.		
MATERIAL	3594800.			0.		
SUBCONTRACTS	33000.			2784658.		
TOTAL DIRECT COST			11151422.			5865386.
PLANT AND EQUIPMENT						
PURCHASE COST	6884750.			4003396.		
SALVAGE	4256465.			2837328.		
NET COST		2628285.			1166068.	
RENT	3000.			24000.		
FREIGHT IN AND OUT	170000.			347000.		
ERECTION AND REMOVAL	399000.			265000.		
SUBTOTAL OTHER THAN PURCHASE		572000.			636000.	
TOTAL PLANT AND EQUIPMENT			3200285.			1802068.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			14351707.			7667455.
INDIRECT COST						
OVERHEAD LABOR	1253734.			0.		
MISCELLANEOUS JOB EXPENSE	532080.			0.		
INSURANCE AND TAXES	1294409.			300433.		
TOTAL INDIRECT COST			3080223.			300433.
TOTAL		69. PERCENT	17431930.		31. PERCENT	7967887.
TOTAL JOB COST						25399816.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						317.

LONG TERM STEEP CONVEYOR — SUMMARY (DOLLARS) — PAGE 1

TABLE 39. COST ESTIMATE, RAIL/SPIRAL CONVEYOR, FAR TERM

LT RAIL/SPIRAL CONVEYOR — ESTIMATOR HVS — DATE 09/23/77

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	2232946.			1617422.		
EQUIPMENT REPAIR LABOR	308230.			476510.		
EQUIPMENT PARTS AND SUPPLIES	2121439.			770626.		
SUPPLIES	2861006.			129412.		
MATERIAL	3594800.			0.		
SUBCONTRACTS	33000.			2778058.		
TOTAL DIRECT COST			11151422.			5772029.
PLANT AND EQUIPMENT						
PURCHASE COST	6884750.			4153500.		
SALVAGE	4256465.			2937898.		
NET COST		2628285.			1215602.	
RENT	3000.			24000.		
FREIGHT IN AND OUT	170000.			347000.		
ERECTION AND REMOVAL	399000.			291000.		
SUBTOTAL OTHER THAN PURCHASE		572000.			662000.	
TOTAL PLANT AND EQUIPMENT			3200285.			1877602.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			14351707.			7649631.
INDIRECT COST						
OVERHEAD LABOR	1253734.			0.		
MISCELLANEOUS JOB EXPENSE	532080.			0.		
INSURANCE AND TAXES	1294409.			308562.		
TOTAL INDIRECT COST			3080223.			308562.
TOTAL		69. PERCENT	17431930.		31. PERCENT	7958193.
TOTAL JOB COST						25390122.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						317.

LT RAIL/SPIRAL CONVEYOR — SUMMARY (DOLLARS) — PAGE 1

TABLE 40. COST ESTIMATE, RAIL/COVERED BELT, FAR TERM

LT RAIL/COVERED BELT, PINCH — ESTIMATOR HVS — DATE 09/23/77

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	2214345.			1592599.		
EQUIPMENT REPAIR LABOR	306714.			465414.		
EQUIPMENT PARTS AND SUPPLIES	2097271.			760076.		
SUPPLIES	2857787.			124478.		
MATERIAL	3594800.			0.		
SUBCONTRACTS	33000.			2777246.		
TOTAL DIRECT COST			11103917.			5719815.
PLANT AND EQUIPMENT						
PURCHASE COST	6884750.			3783500.		
SALVAGE	4256465.			2689998.		
NET COST		2628285.			1093502.	
RENT	3000.			24000.		
FREIGHT IN AND OUT	170000.			347000.		
ERECTION AND REMOVAL	399000.			247000.		
SUBTOTAL OTHER THAN PURCHASE		572000.			618000.	
TOTAL PLANT AND EQUIPMENT			3200285.			1711502.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			14304202.			7431315.
INDIRECT COST						
OVERHEAD LABOR	1253734.			0.		
MISCELLANEOUS JOB EXPENSE	532080.			0.		
INSURANCE AND TAXES	1293040.			284004.		
TOTAL INDIRECT COST			3078854.			284004.
TOTAL		69. PERCENT	17383056.		31. PERCENT	7715319.
TOTAL JOB COST						25098375.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						314.

LT RAIL/COVERED BELT, PINCH — SUMMARY (DOLLARS) — PAGE 1

TABLE 41. COST ESTIMATE, RAIL/BUCKET ELEVATOR, FAR TERM

LT RAIL/BUCKET ELEVATOR — ESTIMATOR HVS — DATE 09/22/77

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	2232946.			1619548.		
EQUIPMENT REPAIR LABOR	308230.			470355.		
EQUIPMENT PARTS AND SUPPLIES	2121439.			771053.		
SUPPLIES	2861006.			129995.		
MATERIAL	3594800.			0.		
SUBCONTRACTS	33000.			2778261.		
TOTAL DIRECT COST			11151422.			5769211.
PLANT AND EQUIPMENT						
PURCHASE COST	6884750.			3619500.		
SALVAGE	4256465.			2580118.		
NET COST		2628285.			1039382.	
RENT	3000.			24000.		
FREIGHT IN AND OUT	170000.			347000.		
ERECTION AND REMOVAL	399000.			254000.		
SUBTOTAL OTHER THAN PURCHASE		572000.			625000.	
TOTAL PLANT AND EQUIPMENT			3200285.			1664382.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			14351707.			7433593.
INDIRECT COST						
OVERHEAD LABOR	1253734.			0.		
MISCELLANEOUS JOB EXPENSE	532080.			0.		
INSURANCE AND TAXES	1294409.			274625.		
TOTAL INDIRECT COST			3080223.			274625.
TOTAL		69. PERCENT	17431930.		31. PERCENT	7708218.
TOTAL JOB COST						25140147.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						314.

LT RAIL/BUCKET ELEVATOR — SUMMARY (DOLLARS) — PAGE 1

13. ESTIMATES FOR HYDRAULIC SYSTEMS

The transportation of solid materials in slurry form through pipelines has been successfully applied to the movement of material, particularly coal, in overland transport and mining operations. Using hydraulic transport in tunneling has been suggested frequently as a promising muck transport method.

SYSTEM DESCRIPTION

The first problem encountered in conceptualizing hydraulic transport systems is a practical means for transporting muck from the mole into the hydraulic loader at the rates envisioned for the near term and far term cases. Each time the loader is moved forward to keep up with the advancing mole, the pipeline must either be drained, or filled with water to displace the slurry. Additional pipes must be installed along with shutoff valves and pumps. Also, if the pipeline is filled with water during the time new pipe sections are being added, additional valves suitably placed may be needed to prevent flooding. In view of the amount of time required for these operations, it was concluded that they should be performed on Saturday (when moling is not in progress) or at times when excavation is halted for some other reason.

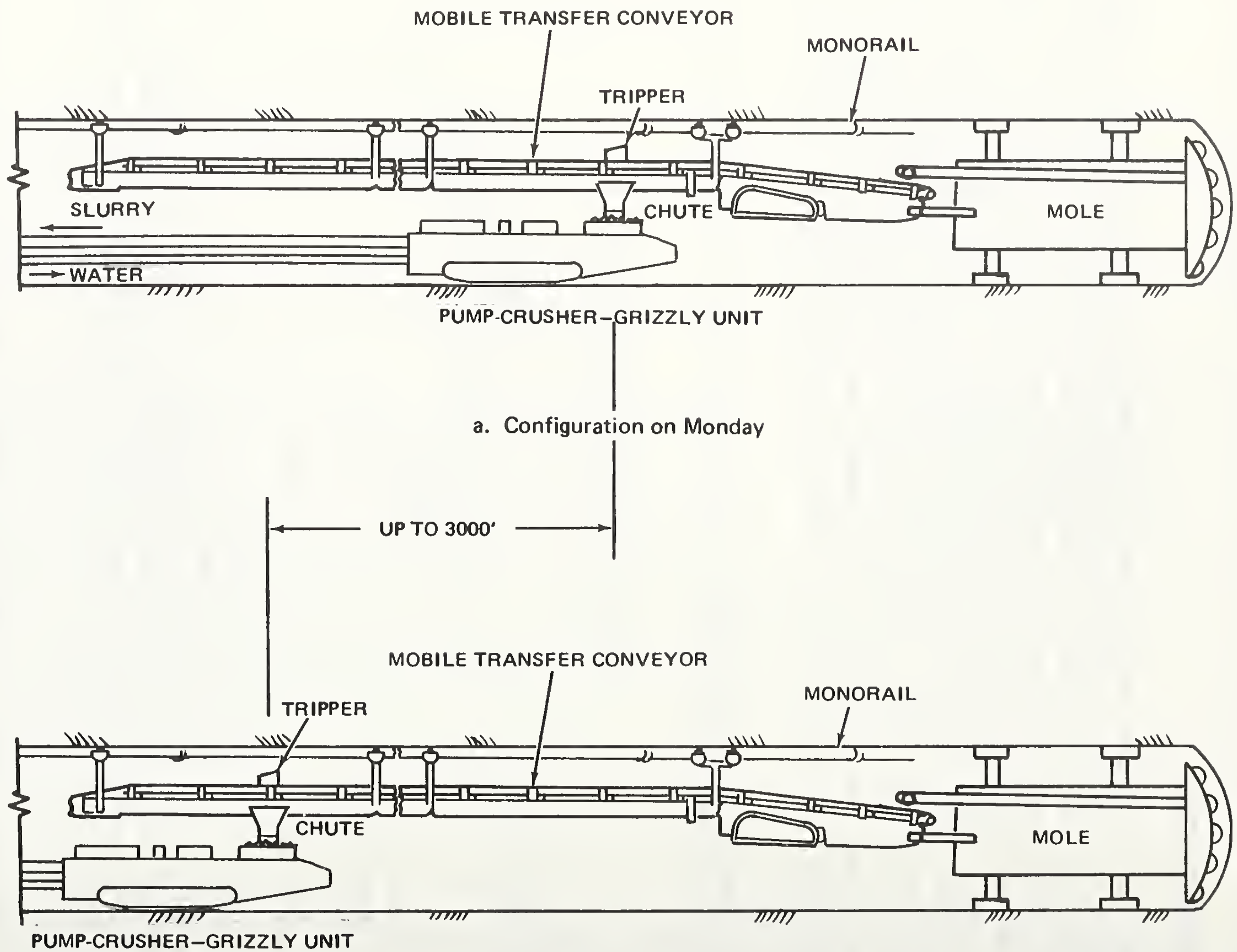
The average and upper limit advance rates for the five-workday week were taken as indicated in Table 42.

TABLE 42. WEEKLY ADVANCE RATE

TIME PERIOD	ADVANCE (Tunnel Feet/Week)	
	Average	Upper Limit
Near Term	600	1,200
Far Term	1,500	3,000

In order to sustain these weekly average advance rates and provide for weeks when the advance is more than average, an extensible conveyor system would be installed between the mole and the hydraulic system loader to carry muck for distances up to the upper limit of weekly advance. The conveyor system selected is supported on an overhead monorail and estimated to cost $500 per foot.

At the start of moling 100-foot conveyor sections and a hoist will be used to transport muck without the hydraulic system. After penetrating a distance sufficient to accommodate the extensible conveyor, the hydraulic system would be installed. Figure 23 shows the positions of the loader, extensible conveyor and mole on Mondays and Fridays. On Saturday the



a. Configuration on Monday

b. Configuration on Average Friday

FIGURE 23. EXTENSIBLE CONVEYOR FEEDING HYDRAULIC SYSTEM

pipes, pump, loader and crusher are moved from the Friday to the Monday configuration.

In the near term case, straight extensible conveyor sections up to 1500 feet long mounted on either wall brackets or a monorail will be used in sections of the tunnel that are not curved. In the curved tunnel sections, conveyor sections 100 feet long will be placed in series to round the turn. In the far term case, it is assumed that a flexible conveyor mounted on a monorail will be available for use as the extensible conveyor and will function in both straight and curved segments of the tunnel.

In both the near term and far term cases, the extensible conveyor system feeds a fixed conveyor through a tripper and chute. The fixed conveyor feeds a series of two grizzlies which separates the oversize muck into a rock box, the mid-size through a crusher, and the undersize to the slurry mixing tank with the crushed rock. After being mixed, the slurry enters a high pressure system and is pumped the length of the tunnel and up a shaft to the surface. Booster pumps placed along the line compensate for the friction losses. At the surface, a dewatering unit with dewatering screens and hydrocyclones separates the solids from the liquid and stores the solids in a surge tank for surface transport to a disposal site. The liquid, with water added to compensate for losses, is returned to the mixing tank through a separate pipeline. Although the volume rate of the return line is less than the volume rate in the slurry line, no significant economies could be found by using a pipe with a smaller diameter or pumps with less horsepower in the return system. Because of this, and in order to simplify logistics and maintenance, pipes of the same diameter and pumps of the same type and size were used in both the slurry line and return line.

SLURRY CHARACTERISTICS

Before sizing the pipeline and pumps, the engineering characteristics of the muck, slurry and return liquid must be determined. The specific gravity of the muck particles will, in practice, depend upon the nature of the rock and will generally vary from section to section of the tunnel. The value for specific gravity is an important parameter because with higher specific gravity, higher slurry velocity and associated higher pump power are needed to keep the solid particles from settling to the bottom of the pipeline and inhibiting the flow. As a representative value, muck with a specific gravity of 2.65 and negligible moisture content was used.

Consideration was also given to the concentration of solids in the slurry. This concentration is usually expressed as percent solids by weight, C_w, and percent solids by volume, C_v. If the slurry is excessively dilute, pumps with large capacities and pipes with large diameters are needed to handle the volume flowing in the pipeline. The costs of such a system would be high. On the other hand, if the slurry is excessively concentrated, the frictional forces rising at the liquid/pipe boundary become excessively high, and the costs of pumps and power become great. A best design point intermediate between the two extremes always exists for these slurries, with the exact location of the best compromise depending upon many factors such as the muck characteristics, availability and cost of water, and cost of electric power. As a reasonable compromise a concentration by weight of 45% was selected.

With the value for the specific gravity of the muck and concentration by weight in the slurry defined, other engineering parameters can be derived by the following equations (53):

$$S_m = \frac{1}{1 + \frac{C_w}{100}\left(\frac{1-S}{S}\right)} \qquad 13.1$$

$$C_v = C_w \times \frac{S_m}{S} \qquad 13.2$$

where S_m = specific gravity of slurry

C_w = percent solids by weight

S = specific gravity of the muck (2.65)

C_v = percent solids by volume

The numerical values found for the slurry specific gravity, S_m, and slurry percent solids by volume, C_v, were 1.39 and 23.6 percent, respectively. These values, along with data for other quantities, are summarized in Table 43.

The volume flow rate of the solids was calculated from the relation

$$F_m = 3.9933 \frac{W}{S} \qquad 13.3$$

where F_m = flow rate of muck in gallons per minute

W = muck rate in tons per hour

3.9933 = a conversion constant with dimensions of gallons per minute divided by tons per hours.

The volume flow rate of the slurry was calculated from the relation

$$F_s = \frac{F_m}{C_v} \times 100 \qquad 13.4$$

where F_s = flow rate of the slurry in gallons per minute

TABLE 43. CHARACTERISTICS OF HYDRAULIC CASES

	Item	Units	Near Term		Far Term	
			Slurry Line	Return Line	Slurry Line	Return Line
1	Thruput of Solids	tons/hour	400	-	900	-
2	Specific Gravity of Solids	-	2.65	2.65	2.65	2.65
3	Percent of Solids by Weight	percent	45.00	14.6	45.0	14.6
4	Percent of Solids by Volume	percent	23.59	6.1	23.59	6.1
5	Specific Gravity	-	1.3893	1.0	1.3893	1.0
6	Flow Rate of Solids	USGPM	602.8	-	1357	-
7	Flow Rate of Liquid	USGPM	1952	1952	4393	4393
8	Flow Rate of Slurry	USGPM	2555	-	5730	-
9	Pipe Diameter	inches	8	8	12	12
10	Minimum Velocity	ft/sec	13.8	0	14.43	0.
11	Actual Velocity	ft/sec	16.31	12.46	16.31	12.46
12	Friction Factor	percent	1.54	1.55	1.41	1.41
13	Maximum Pipe Length	feet	10,120	10,120	40,220	40,220
14	Friction Head Loss	feet	966	567	2342	1367
15	Lift to Surface	feet	120	120	220	220
16	Static Head Loss	feet	180	-120	330	-220
17	Total Head Loss	feet	1146	447	2672	1147
18	Pump Derating Factor	-	0.34	0.0	0.34	0.0
19	Ratio: Slurry Head/Water Head	-	0.5990	1.00	0.5990	1.00
20	Pump Head with Water	feet	190	198	213	213
21	Pump Head, Operating Liquid	feet	114	198	128	213
22	Maximum Number of Pumps	-	10	3	21	6
23	Average Power of Each Pump	hp	160	160	300	300
24	Maximum Power of Each Pump	hp	350	350	600	600
25	Total Average Power	hp	1,600	480	6,300	1,800
26	Total Peak Power	hp	3,500	1,050	12,600	3,600

The numerical values for these quantities are summarized on lines 6, 7, and 8 of Table 43.

RETURN LIQUID

The return liquid comes in part from the slurry after processing through a dewatering unit and in part from additional water added to compensate for the water removed with the muck. Faddick and Martin (25) have outlined a method for developing return water that is almost free of muck and has a specific gravity of 1.0 and values of C_w and C_v equal to zero. These values were adopted for the return water.

The flow rate of the return liquid, F_L, in gallons per minute, is calculated from the relation

$$F_L = F_s - F_m \tag{13.5}$$

SLURRY VELOCITY

Slurries with large, dense, solid particles that settle when the velocity is low, require turbulence to keep the particles suspended. In situations where particles are small and the concentration of solids is almost homogeneous, the operation is efficient. This mode of operation is used for long-distance pipelines but is generally not achievable in tunnel applications where particles have high specific gravity and coarse mesh size. Under these conditions particles tend to settle to the bottom of the pipe. High velocity and high turbulence are required to keep the particles in suspension. When a slurry system operates at a velocity below the critical one, the particles tend to collect along the bottom of the pipe, which may lead to pipeline plugging. This critical velocity, V_c, is given by the relation (53)

$$V_c = F \left[\frac{2g(S-S_r)D}{12S_r}\right] \tag{13.6}$$

where F = dimensionless constant, equal to 1.4 for large particles (53)

D = pipe diameter (inches)

g = acceleration of gravity (32.2 ft/sec^2)

S_r = specific gravity of the liquid

S = specific gravity of the solids

The slurry velocity can be calculated from the volume flow rates and must exceed the critical velocity. Table 44 contains, as a function of pipe diameter, data for the critical velocity, V_c, and the slurry throughput velocity, V_s, for the near and far term cases. As can be seen from the table, pipe diameters of 9 inches or less for the near term and 12 inches or less for the far term cases will satisfy the requirement that V_s exceed V_c. Pipe diameters of 8 and 12 inches were selected for the near and far term cases, giving a velocity of 16.3 feet per second in both cases.

TABLE 44. CRITICAL VELOCITY AND THRUPUT VELOCITY

Pipe Diameter (Inches)	Critical Velocity, V_c (ft/sec)	Thruput Velocity, V_s, (ft/sec) Near Term (2555.2 gpm)	Thruput Velocity, V_s, (ft/sec) Far Term (5749.2 gpm)
7	11.022	21.303	47.931
8	11.783	16.310	36.697
9	12.496	$\boxed{12.887}$	28.995
10	13.174	10.436	23.486
11	13.817	8.627	19.410
12	14.432	7.249	$\boxed{16.310}$
13	15.021	6.176	13.897
14	15.588	5.326	11.983

RETURN LIQUID VELOCITY

For practical purposes, all solid particles have been removed from the return liquid. Therefore, the critical velocity is zero. The velocity of the return liquid (see Table 43, line 11) was determined from the volume flow rate and the pipe cross sectional area.

FRICTIONAL LOSSES

Fluids flow in pipes because the pressure gradient overcomes the frictional losses of the flowing fluid. In the region of turbulent flow, the frictional loss and pressure gradients are a rapidly increasing function

of velocity. The Darcy-Weisback equation (7) is used frequently to calculate frictional losses and takes the form

$$H = \frac{6fv^2L}{gD} \qquad 13.7$$

where H = pressure loss in feet of head for the liquid flowing

f = friction factor, feet loss/foot pipe

L = pipe length in feet

v = liquid velocity in feet per second

D = pipe diameter in inches

g = acceleration of gravity (32.2 ft/sec^2)

Excepting f, the quantities in equation 13-7 are readily determined from the dimensions of the pipeline and the volume flow rate. Two methods of estimating values for f are presented here. The frictional losses, static head and pump head will all be expressed in units of feet head of slurry in the slurry line and as feet head of water in the return line.

Graphical Method for Estimating Friction Factor

The graphical method used is based upon material provided by Brown (5) and Moody (56). To use Figure 24 one needs the Reynolds number, Re, and the relative pipe roughness, ε/D. The Reynolds number is given by the well known relation

$$Re = \frac{Dv\rho}{\mu}$$

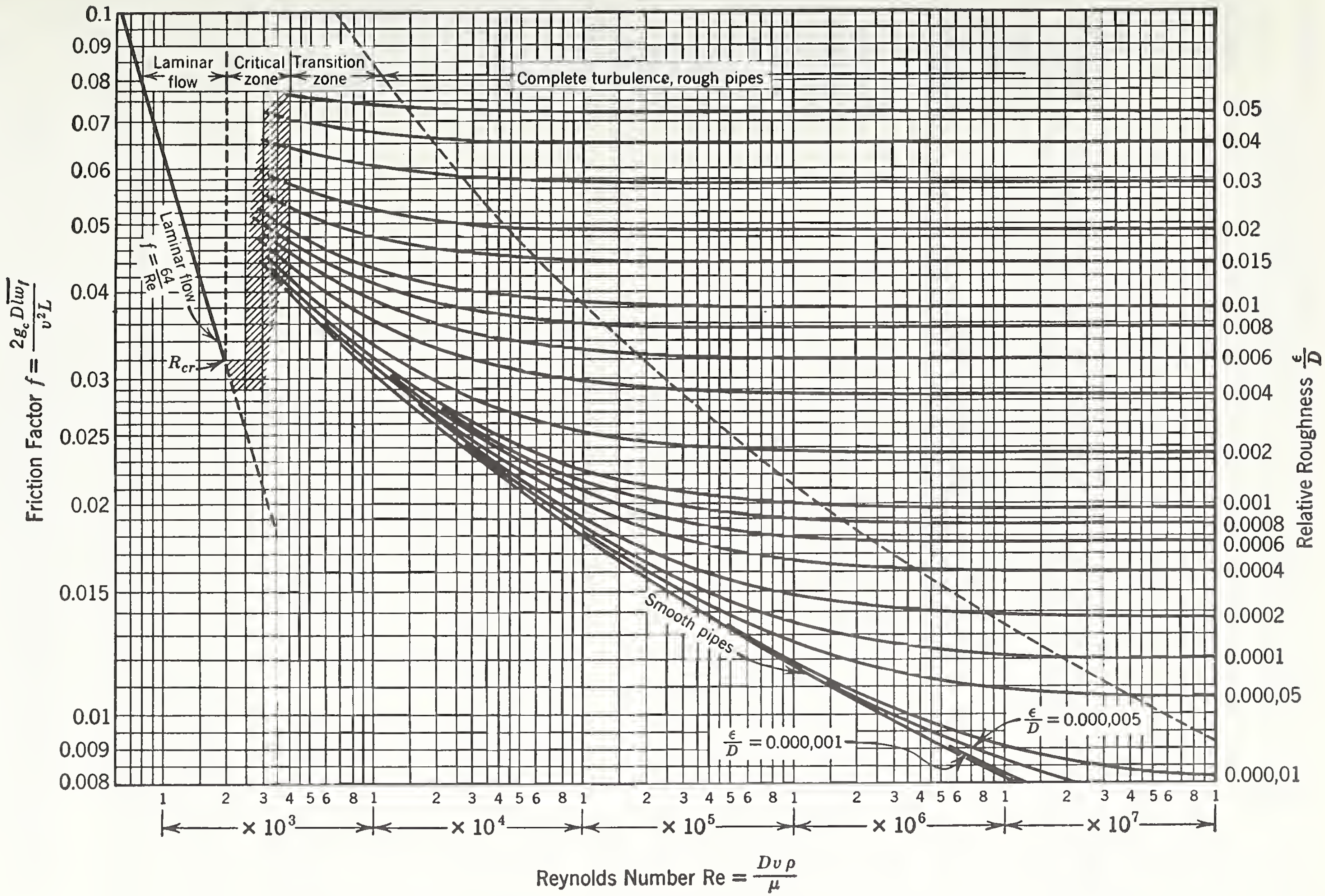
where ρ = density D = pipe diameter

μ = viscosity v = fluid velocity

Since Re is dimensionless, the equation is valid in any consistent set of units. The relative pipe roughness is given by the empirical relation

$$\frac{\varepsilon}{D} = \frac{1.8 \times 10^{-3}}{D}$$

Data applicable to the near and far term cases are presented in Table 45. These data are based upon a fluid with the viscosity of water (1.1 cp); a reasonable value for the return liquid. The slurry will have a higher value, but how much higher is a matter of speculation.



Source: Brown (5) after Moody (56); Courtesy Estate of Lewis Ferry Moody

FIGURE 24. FRICTION FACTOR

Dallavalle (17) observed a curious fact regarding slurries; that for all substances studied a nearly linear relation existed between solids concentration by volume, C_v, and the apparent viscosity in the range of C_v between 0 and 25 percent. Above this region the viscosity increased rapidly with increasing concentration of solids. His observation was one of the determinants used in this work for selecting a value for C_v near 23 percent. Some of his published curves suggest a value for viscosity of about 10 cp would be more typical for the slurry than 1.1. If this were the case, then the Reynolds number for the flow would be smaller by a factor of 9, and the friction factor increased to 0.018 to 0.020 as read on Figure 24. This would tend to increase the number of pumps and pumping power required.

TABLE 45. FRICTION FACTOR

	Near Term		Far Term	
	Slurry Pipeline	Return Pipeline	Slurry Pipeline	Return Pipeline
Fluid Density (lbs/ft^3)	86.5	62.4	86.5	62.4
Pipe Diameter (in)	8.0	8,0	12.0	12.0
Velocity (ft/sec)	16.31	12.46	16.31	12.46
Reynolds Number ($\mu = 1.1$ cp)	1.3×10^6	6.9×10^5	1.9×10^6	1.4×10^6
Relative Pipe Roughness (Commercial Steel), ε/D	2.3×10^{-4}	2.3×10^{-4}	1.5×10^{-4}	1.5×10^{-4}
Friction Factor	.0154	.0155	.0141	.0141
Friction Head Loss (ft liquid/ft pipe)	.0954	.0560	.0582	.0337

Williams and Hazen Relation

The Williams-Hazen formulation (7) for the friction head loss has been used widely and often in the convenient form

$$H/L = 0.002083 \left(\frac{100V}{C}\right)^{1.85} \left(\frac{1}{D^{4.8655}}\right) \qquad 13.8$$

Where H/L = friction head loss (ft head/ft pipe)

C = constant expressing pipe roughness

V = flow rate (USGPM)

D = inside pipe diameter (inches)

For new weld or seamless steel pipe C is 140. Using the values previously determined for C, V, and D, the friction factor and head loss can be calculated from equations 13-8 and 13-7. The total head loss (line 17, Table 43) is the frictional head loss plus the static head loss (gain for return line) for the rise to the surface.

Comparison of Methods for Estimating Head Loss

The head losses determined by the Williams-Hazen and graphical methods are summarized in Table 46 and compared to the values obtained from the Moody graph (Figure 24) for a hypothetical slurry with viscosity of 10 cp. The graphical head losses for water are less than 6 percent greater than calculated by the Williams-Hazen relation. Increasing the viscosity to 10 cp increases the head loss about 24 percent. In order not to penalize the hydraulic systems because of some unknown discrepancy in estimating head loss, the smaller value (that for water) for each pipeline was used in determining the pump requirements and pipeline system costs. This procedure under estimates friction losses, the number of slurry pumps, and the cost of the hydraulic systems.

TABLE 46. COMPARISON OF HEAD LOSS

	Head Loss per Foot			
	Near Term		Far Term	
Method of Calculating Friction Loss	Slurry Pipeline	Return Pipeline	Slurry Pipeline	Return Pipeline
Williams-Hazen	.09084	.055198	.056607	.034412
Graphical for Water ($\mu = 1.1$ cp)	.0954	.0560	.0582	.0337
Graphical for Slurry ($\mu = 10$ cp)	.118	.0560	.0722	.0337

It should be emphasized that the computation of frictional head loss in horizontal and vertical pipes and static head in vertical pipes is not an exact science. In practice, before a slurry line is designed, tests are conducted to determine experimentally the engineering parameters required

to design an operational system. Here, the work has proceeded with published equations and average values for parameters without the benefit of tests.

VERTICAL LIFT

In vertical lift, the particles move upward more slowly than the liquid flows, because the particles settle under the influence of gravity. Since the continuity of flow of both the liquid and the solids is maintained throughout the pipe, the concentration of solids increases in vertical lift sections in comparison with that in horizontal sections. The procedures commonly used to correct for settling involve the distribution of particle size and drag coefficients. This level of detail would be required in designing an installation, but is not needed in this feasibility work. The problem of settling was resolved by providing about 50 percent excess lifting head at the base of the vertical pipeline segment.

PUMPS

Pumps are required in sufficient number to overcome the frictional and static head losses (line 17, Table 43). For study purposes, two sizes of centrifugal pumps, one for the near term case and one for the far term case, were selected with characteristics provided by Warman International, Inc., as shown on Figure 25. The pumps and controls are recessed into the walls of the tunnel to maintain an open passage through the tunnel.

The pressure heads developed with water flowing at the estimated throughput rates would be 190 feet for the near term case with the 8/6 FAH pump and 212 feet for the far term case with the 12/10 GAH pump. Pressure heads of this magnitude would be developed on the return line, for the return liquid has characteristics approximately that of water. On the slurry line, the head ratings (HR) of the pumps are degraded by a factor 0.5990 (see Figure 26) for the muck specific gravity of 2.65, so that pumps on the slurry line develop heads of 114 and 121 feet for the near and far term cases. With these head ratings and specific gravity of 1.389 for the slurry, the pump pressures are 69 and 75 psi, respectively.

The vertical lift exceeds the head developed by one centrifugal pump, so two pumps were used in series, appropriately placed along the tunnel. In an actual design, greater consideration would be given to using reciprocating pumps to provide the head necessary for the vertical lift. However, the cost savings (if any) would be small in comparison with the overall costs and would be barely observable in the final costs. For this reason, centrifugal pumps were used.

Table 47 compares the number of pumps required based on the Moody graphical method using water and slurry viscosities, and on the Williams-Hazen equation. The higher viscosity (10 cp) requires 20 percent more pumps than required if the viscosity of water is assumed. Costs for the hydraulic systems were based on the smaller number of pumps.

TABLE 47. PUMPS REQUIRED

Method of Calculating Friction Loss	Number of Pumps			
	Near Term		Far Term	
	Slurry Pipeline	Return Pipeline	Slurry Pipeline	Return Pipeline
Graphical (water)	10	3	21	6
Williams-Hazen	10	3	21	6
Graphical (Slurry)	12	3	25	6

SURFACE EQUIPMENT

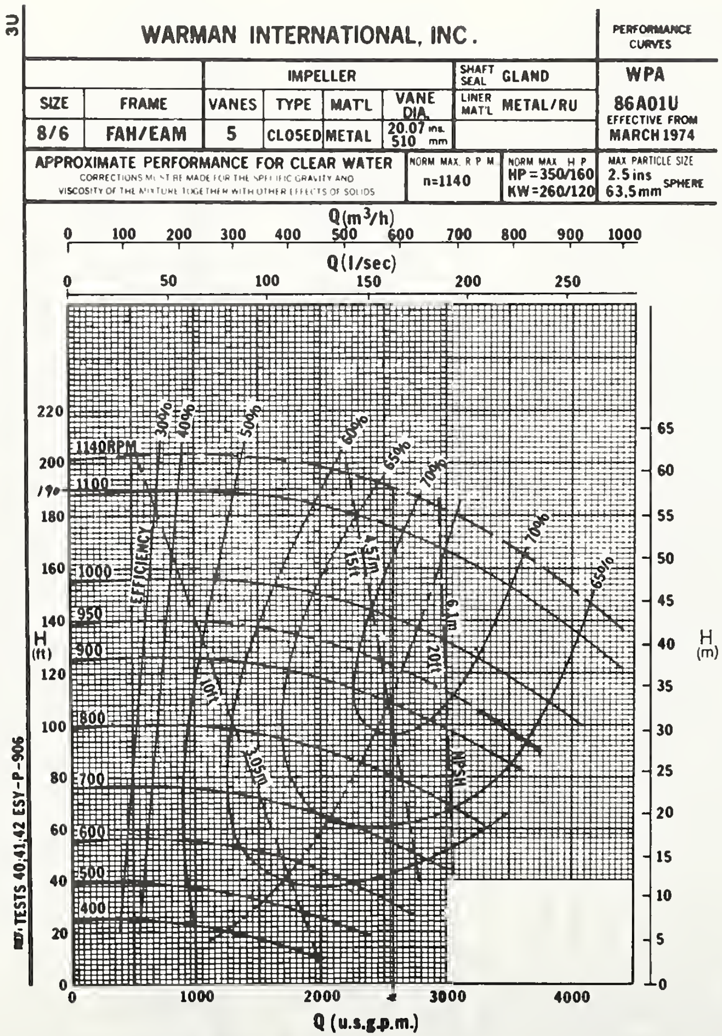
The surface pipeline equipment consists primarily of a dewatering unit to separate the solids from the liquid, and equipment to process the liquid to a water quality adequate for return to the loader. Faddick and Martin (24, 25) studied a number of systems for accomplishing this task. Their systems for coarse slurries involved vibrating screens, hydrocyclones, rubber screens, thickeners, tanks, pumps, and motors. Figure 27 contains a reproduction of their general flow sheet and Figure 28 shows their numerical calculations of the flow for a dewatering system processing 45 percent by weight slurry containing 382 tons per hour of solids (reasonably close to the near term case). With this equipment the dewatered muck is in a form suitable for surface transport and the liquid is suitable for reclycing.

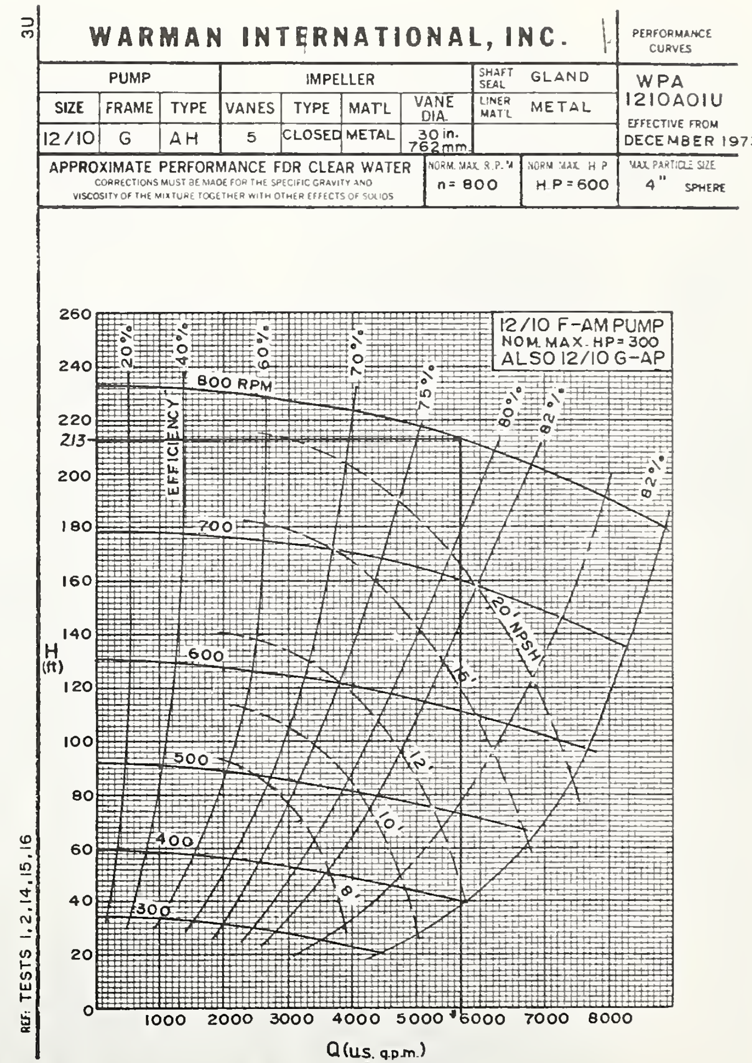
A system somewhat similar to that postulated by Faddick and Martin was scaled up in size to meet the muck and slurry rates of the near and far term cases.

INBOUND TRANSPORT SYSTEM

A minimal rail system was assumed to be installed to carry men, supplies, and equipment from the shaft to the heading. The equipment, manpower, and costs associated with this system were derived from those presented in Section 11.

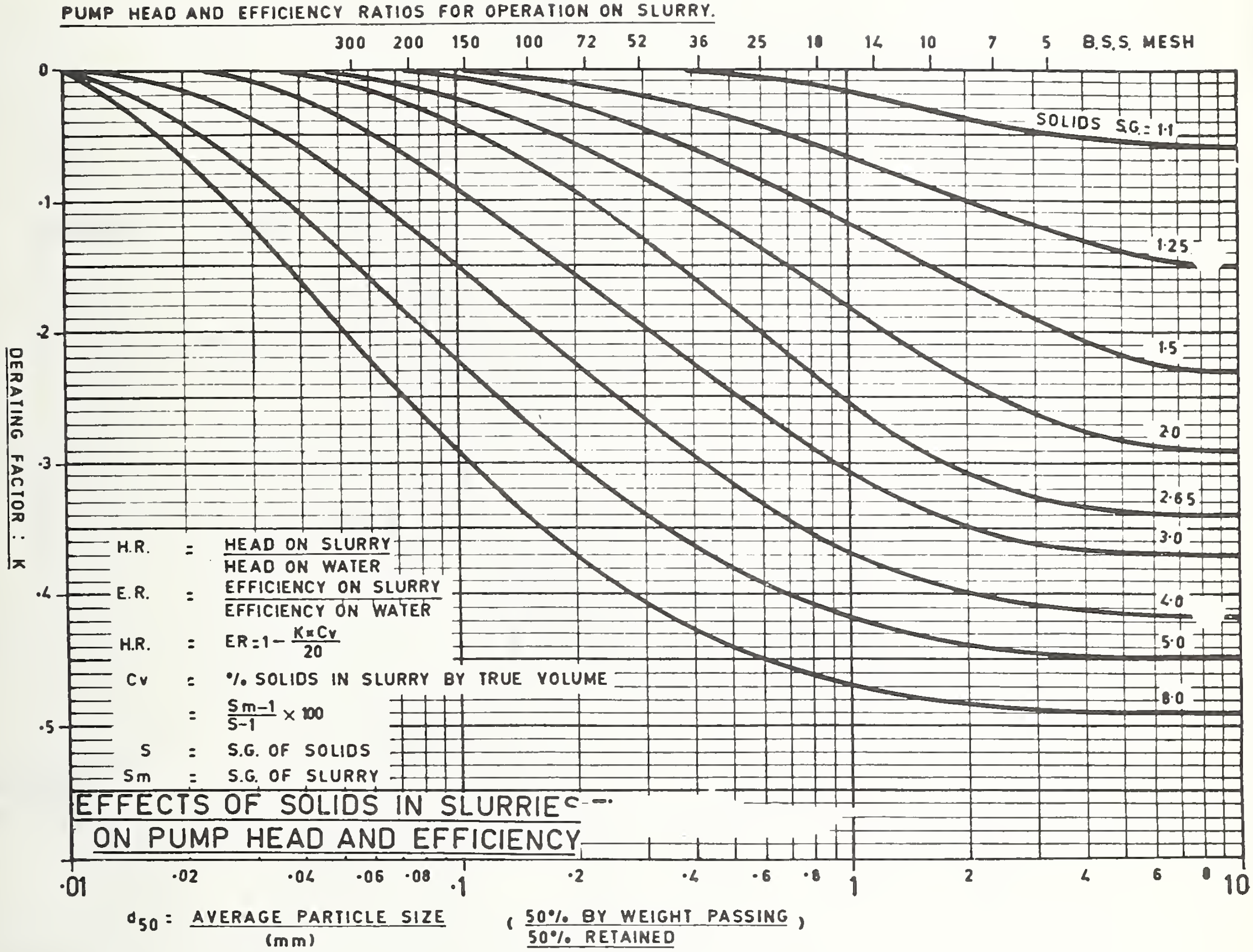
A special rail car with a small crane would be required to handle the hydraulic pipe. Since no such vehicle is currently in operation, this would be a new type of vehicle.





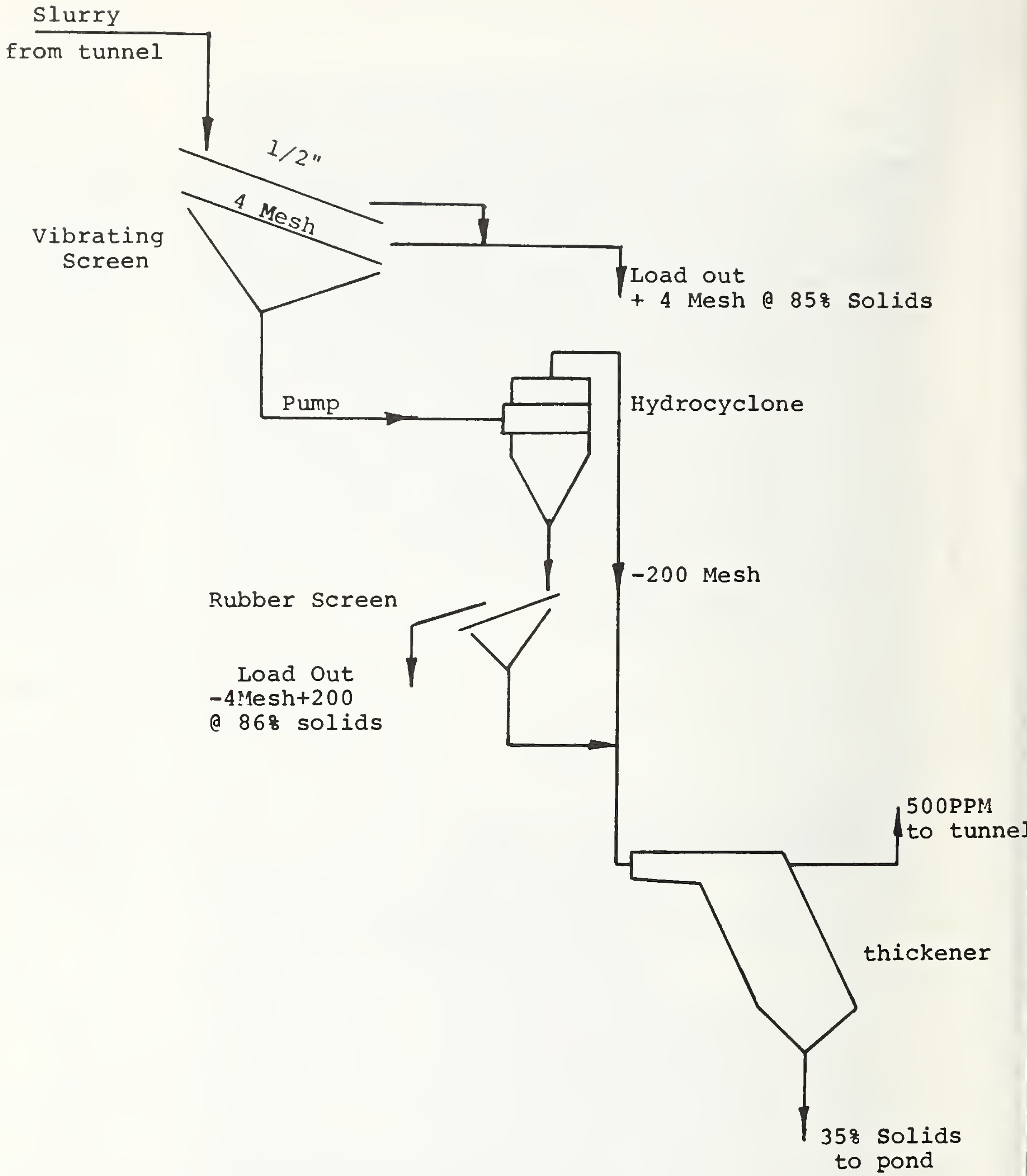
Source: Warman International

FIGURE 25. PUMP SELECTION



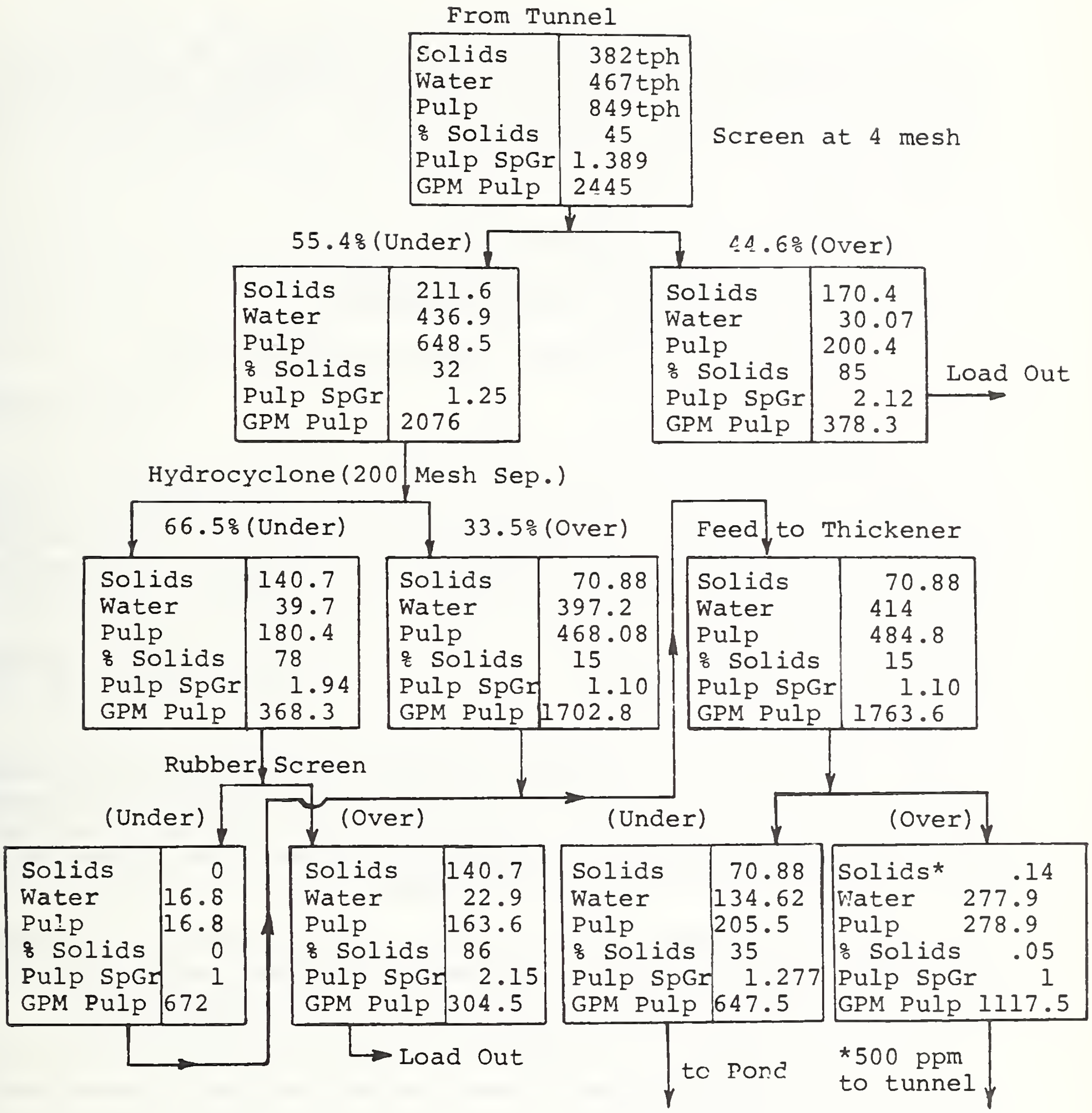
Source: Mc Elvain, R. E., (53), Skillings' Mining Review, Jan. 26, 1974

FIGURE 26. PUMP HEAD AND EFFICIENCY RATIOS FOR OPERATION ON SLURRY



Source: Faddick and Martin (25)

FIGURE 27. GENERAL FLOW SHEET FOR DEWATERING TUNNEL MUCK



Source: Faddick and Martin (25)

FIGURE 28. MATERIAL BALANCE FOR SLURRY SURFACE EQUIPMENT

COSTS

Equipment Costs

The major elements of the hydraulic system including loaders, pipe, pumps, and dewatering units were costed on the basis of data provided by Faddick and Martin (24, 25) with a factor of 1.6 applied to the 1974 costs for escallation to 1978. Table 48 summarizes the costing for the equipment.

Personnel Costs

The major elements of manpower costs are:

a. Pay scale for each job classification

b. Number of men assigned to each job classification

c. Number of shifts that each job is manned over the entire job duration.

Although many of the job titles for the hydraulic systems are usually not found on tunnel projects, the type of work is similar to other jobs that are familiar in the field. A set of job titles was prepared for the positions needed to operate the hydraulic equipment and a pay scale assigned on the basis of similarity to an existing job. Other men were added to fill the more usual jobs, like operating the rail line, and pay scales assigned to them. Table 49 shows the jobs by title, the rate per shift for each job, and the number of men in each job.

The rail system will transport equipment and supplies into the tunnel and transport equipment out. The amount of traffic can be handled on one shift on week days, so only one crew is provided for the rail and crane systems during the week. The hydraulic system will operate three shifts per day so three crews are provided for this operation.

On Saturdays, manpower will be needed on three shifts to extend the pipeline, move the loader and install pumps. The Saturday crew is larger for the hydraulic system than that selected for ràil and conveyor systems.

The crew to remove the hydraulic pipeline and the fan line after the excavation is finished is larger than the crew required to remove the fan line alone for other systems.

Moling Time and Job Duration

The number of moling hours was estimated from the number of tunnel feet and the average penetration rate, and the total excavation duration from the moling time plus the delay times.

The estimates for the moling and delay times for the near term and far term hydraulic pipeline systems using a conveyor system between the mole and the pipeline feed are summarized in Table 50.

Other Costs

The electric power system for the hydraulic pumps constitutes a substantial cost, as large amounts of power will be required to operate the system continuously and provide the additional power required to overcome startup inertia. The costs incurred in establishing and operating the electric power system are itemized separately in the cost estimate and allocated entirely to the material handling system. The power costs were estimated as $0.06 per horsepower hour for the horsepower requirement from line 25 of Table 43 assuming that, averaged over the period of excavation, half the maximum number of pumps would operate. The electrical power installation costs were scaled from the cost estimates prepared for the base case, basing the material handling power requirements was examined for the near term upon the total peak horsepower requirements from line 26 of Table 43, and ratioed in proportion to the peak power required for the mole.

Computer Costing

The elements of data for costing the job with a computer program are discussed in Appendix B. The major cost elements developed by the methods indicated were entered into the computer, which produced the cost breakdown for the near and far term cases as summarized in Tables 51 and 52. The costs per tunnel foot for the near and far term hydraulic cases are $596 and $383 per tunnel foot, respectively.

PNEUMATIC-HYDRAULIC SYSTEM

An alternative to the conveyor system for transporting muck from the mole to the hydraulic feed point is a pneumatic system. This alternative case was examined for the near term by two costing methods without making direct cost estimates for a 400 tph pneumatic-hydraulic system:

a. Costs were scaled-up from an estimate previously made for a 220 tph pneumatic-hydraulic system.

b. The cost difference was obtained for two 400 tph systems, one with a conveyor transporting muck 1000 feet horizontally and feeding a pneumatic lift, and the other with pneumatic transport 1000 feet horizontally and feeding a pneumatic lift (see Section 14).

Both methods gave results that were in close agreement, differing by about 3 percent. The job cost using the pneumatic-hydraulic system appears to be about 6 percent higher than that using the conveyor-hydraulic system. Faddick (22) has observed that pneumatic and hydraulic pipeline systems would be more attractive, both technically and economically, if the two systems were used independently.

TABLE 48. SLURRY SYSTEM COSTS

Type of Equipment	Formula	Quantity		Cost (1978 Dollars)	
		Near Term	Far Term	Near Term	Far Term
Extendable Conveyor	\$500 per foot	1200 ft	3000 ft	250,000	1,000,000
Grizzly	$1.6 \times 480 (W)^{0.75}$	400 t/h	900 t/h	138,000	120,000
Crusher	$1.6 \times 660 (1/2\ W)^{0.933}$	400 t/h	900 t/h	192,000	200,000
Conveyor with Hopper	\$256 per foot	50	50	13,000	13,000
Pumps with Motor	$1.6 \left[1000 (BHP)^{0.3171} + 70 \times BHP\right]$	15/350 hp	30/600 hp	741,000	2,299,000
Pipes with Fittings	$1.6 \left[19.83 (D/12+0.021)\ L\right]$	8", 20,000 ft	12", 80,000 ft	380,000	2,480,000
Mixing Tank	$1.6 (8000+62.5W)$	400 t/h	900 t/h	53,000	103,000
Loader		1	2	20,000	40,000
Surge Tanks	1.6x2000	1	27	45,000	81,000
Pipe Handler	2.6x30,000	3	3	150,000	150,000
Trailing Floor	\$1000 per foot	-	50	-	50,000
Hydrocyclones	-	-	-	32,000	72,000
Agitation Tank	1.6x5000	1	1	8,000	8,000
Conveyors	\$256 per foot	75	75	19,000	19,000
Dewatering Screens	$1.6 \left[W/425 \times 5600\right]$	400 t/h	900 t/h	18,000	36,000
Surge Tank		1	1	6,000	6,000
Controls		1	1	300,000	300,000

TABLE 49. WORK CREWS, HYDRAULIC SYSTEM

	Rate per Shift (Dollars)	Number of Men on Daily Three Shifts		Number of Men on Saturday Maintenance		Remove Fan and Hydraulic Lines	
		Near Term	Far Term	Near Term	Far Term	Near Term	Far Term
UNDERGROUND							
Materials Handling Equipment Ext.	114	1.5	1.5	-	-		
Hydraulic Supervisor	143	3.0	3.0	2.0	2.0		
Crusher Operator	143	3.0	3.0	1.0	1.0		
Stower-Conveyor Operator	143	3.0	3.0	3.0	3.0		
Pipe Handler Operator	143	1.0	1.0	2.0	6.0	3	3
Pump Operators	143	6.0	9.0	2.0	5.0	6	6
Bull Gang	107	1.5	1.5	1.5	1.5		
Motorman	139	1.0	1.0	1.0	1.0	3	3
Brakeman	107	1.0	1.0	1.0	1.0	3	3
Bottomman	114	1.0	1.0	1.0	1.0	3	3
Shifter	135			-		6	6
Miner	123			-		18	18
Chucktender	114					9	9
Laborer	84					4	4
Pipe Handlers	107	1.0	1.0	6.0	12.0	6	6
SURFACE							
Yard Crane Operator	115	1.0	1.0	1.0	1.0	3	3
Labor Foreman	88	1.0	1.0	1.0	1.0		
Laborers	84	1.0	1.0	3.0	3.0	2	2
Dewatering Unit Operator	111	6.0	6.0	1.0	1.0		
TOTAL CREW		32.0	35.0	27.5	39.5	66	66

TABLE 50. MOLING AND DELAY TIMES
(Hydraulic System)

Item	Time (hours)	
	Near Term	Far Term
Moling	1944	3178
Reset	108	221
Rock Support: Bolts	0	0
Sets	400	427
Materials Handling: Derail	4	0
Connect Vertical Shafts	0	0
Pipe Extensions	0	0
Reset Conveyors	0	0
Pump Line	39	100
Ventilation	39	79
Power: Add Cable	54	78
Outages	8	24
Cutters	97	159
Repairs: Mole	389	636
Material Handling	194	318
Drills	58	95
Other	19	32
Shift Change	156	254
Miscellaneous	456	480
Total Time	3965	6081
Total Time (Days)	165	253

TABLE 51. COST ESTIMATE, HYDRAULIC, NEAR TERM

37 NT HYDRAULIC — ESTIMATOR LAG — DATE 10/17/77

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	1276476.			794634.		
EQUIPMENT REPAIR LABOR	165669.			374918.		
EQUIPMENT PARTS AND SUPPLIES	562102.			249104.		
SUPPLIES	927743.			58478.		
MATERIAL	898700.			0.		
SUBCONTRACTS	33000.			678585.		
TOTAL DIRECT COST			3863691.			2155719.
PLANT AND EQUIPMENT						
PURCHASE COST	3795300.			4691250.		
SALVAGE	2733285.			2826672.		
NET COST		1062015.			1864578.	
RENT	3000.			0.		
FREIGHT IN AND OUT	101000.			210000.		
ERECTION AND REMOVAL	316000.			144000.		
SUBTOTAL OTHER THAN PURCHASE		420000.			354000.	
TOTAL PLANT AND EQUIPMENT			1482015.			2218578.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			5345706.			4374296.
INDIRECT COST						
OVERHEAD LABOR	933792.			0.		
MISCELLANEOUS JOB EXPENSE	356500.			0.		
INSURANCE AND TAXES	599092.			309376.		
TOTAL INDIRECT COST			1889384.			309376.
TOTAL		61. PERCENT	7235089.		39. PERCENT	4683672.
TOTAL JOB COST						11918761.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						596.

37 NT HYDRAULIC — SUMMARY (DOLLARS) — PAGE 1

TABLE 52. COST ESTIMATE, HYDRAULIC, FAR TERM

36 FAR TERM HYDRAULIC — ESTIMATOR LAG — DATE 10/18/77

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	2246301.			1365232.		
EQUIPMENT REPAIR LABOR	306930.			729114.		
EQUIPMENT PARTS AND SUPPLIES	2126539.			2021643.		
SUPPLIES	2862935.			104717.		
MATERIAL	3594800.			0.		
SUBCONTRACTS	33000.			2772978.		
TOTAL DIRECT COST			11170504.			6993684.
PLANT AND EQUIPMENT						
PURCHASE COST	6884750.			10868140.		
SALVAGE	4256465.			6043038.		
NET COST		2628285.			4825102.	
RENT	3000.			0.		
FREIGHT IN AND OUT	170000.			453000.		
ERECTION AND REMOVAL	399000.			178000.		
SUBTOTAL OTHER THAN PURCHASE		572000.			631000.	
TOTAL PLANT AND EQUIPMENT			3200285.			5456102.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			14370789.			12449786.
INDIRECT COST						
OVERHEAD LABOR	1253734.			0.		
MISCELLANEOUS JOB EXPENSE	532080.			0.		
INSURANCE AND TAXES	1294760.			778759.		
TOTAL INDIRECT COST			3080574.			778759.
TOTAL		57. PERCENT	17451364.		43. PERCENT	13228545.
TOTAL JOB COST						30679909.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						383.

14. ESTIMATES FOR PNEUMATIC SYSTEMS

Coal, wood chips, and other industrial substances have been transported successfully by pneumatic systems. Radmark Engineering, Inc., installed pneumatic muck transporting systems in tunnels in Edmonton and Halifax (67). These precedents make pneumatic transport of interest as a candidate for muck transport in future tunnel operations. Therefore, the feasibility of pneumatic transport was explored under the conditions of the near term and far term time periods defined for this study.

Two sets of input data for the computer costing program were developed. One set is based on extrapolation of the flow equations developed by Konchesky, George and Craig (44, 45), and cost data provided by Faddick and Martin (24), updated for escalation. The other data are provided by Radmark Engineering, Inc. (67a) from computer calculations based on a proprietary model and cost data in use for current system pricing. The Radmark data and discussion are provided at the end of this section.

SYSTEM DESCRIPTION

The pneumatic system accepts the muck from the mole without intermediate surge storage, at rates up to 400 and 900 tons per hour in the near and far term cases, respectively (Figure 29). In this arrangement, the grizzlies, crusher, stower and blower are mounted on sleds or wheeled platforms and dragged forward by the mole. The Radmark arrangement places the blowers on the surface. This reduces the underground noise and eliminates the need to extend the electric cable for the blowers. However, power cable extension will be required for the stower and preparation equipment. Placing the blowers on the surface requires that an air feed pipe be provided from the blower to the stower and that it be extended as the mole advances. Added power is required to pump the air through the feed pipe.

Conveyors carry the muck to grizzlies that separate any +12-inch rocks into a rock box, the -12 to +2.5-inch muck to a crusher and the -2.5 material to the loader-stower. An alternative would be to crush to about 1-inch top size to reduce the wear on the stower, but the cost of crushing would increase. For many rock types, the mole would produce particles small enough not to require crushing, thus eliminating the grizzlies and crusher if consistency of the rock type can be assured. The Radmark concept assumes this condition and does not use a crusher.

The relatively small number of large rocks are either transported by rail out of the tunnel or broken with a sledge hammer or hydraulic breaker and passed through the crusher. The crusher, processing up to 50 percent of the muck, delivers a product with a fineness of -2.5 inches (Radmark assumes -2 inches). The pneumatic stower injects the muck into the pressurized system that transports horizontally to a vertical bore hole or small shaft for transport to the surface (Figure 30). On the surface, the muck particles and the dust are removed from the air stream and loaded onto trucks for hauling to the disposal site.

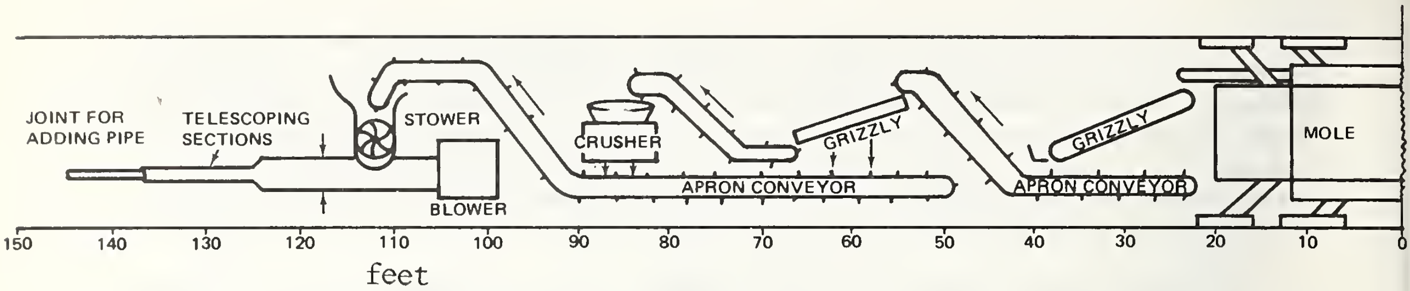


FIGURE 29. PNEUMATIC SYSTEM FEED ARRANGEMENT

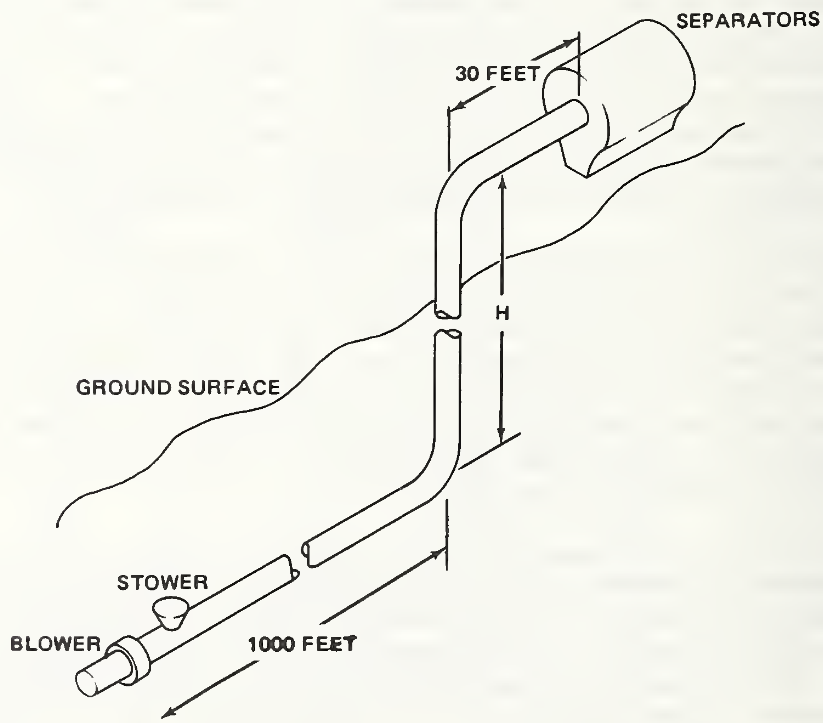


FIGURE 30. PNEUMATIC SYSTEM PIPE PROFILE
(Height of lift, H, is 120 and 220 feet in near and far term cases respectively.

A telescoping extensible pipe section 90 feet long, located downstream of the stower, provides the flexibility needed to keep the major part of the pipeline stationary while the mole advances, dragging the stower and blower along with it. The presently available Radmark design for telescoping sections is 15 feet long; therefore, 7 sections would be required. Faddick and Martin tested two of these sections in series without difficulty but feel that 7 sections may be excessive due to the guide system necessary to maintain alignment and for curve negotiation (23). Perhaps 4 sections could be used. Longer individual sections, up 20 or 40 feet, may be possible but they do not exist presently. At the completion of the maximum excavation, the telescoping pipe sections are retracted, the rails extended and, with the help of a special rail mounted pipe handling car, new sections of pipe are installed to close the gap between the end of the pipe and the telescoping section.

The average advance rate is projected to be 600 feet per week for the near term case and 1500 feet per week for the far term case. Fourteen-inch bore holes (or shafts up to 6-foot diameter for the Radmark concept) are prepositioned every 500 feet (near term) and 1000 feet (far term) in the two cases. If the mole advances past a bore hole during the week, then on the following Saturday the pneumatic pipe is disassembled, the old bore hole grouted for abandonment, and the pneumatic pipe connected to the next hole. In this way the horizontal transport is kept to a maximum of about 1000 feet or less in both the near term and far term cases. It will frequently be necessary to stop the moling and change the pipe arrangement to a new bore hole during the week for the long term case.

The inbound material is transported by a minimal rail system scaled down from the one described in Section 11. Lightweight track will be adequate to carry the light inbound load. Without the need for numerous muck cars, the outbound traffic will be comparatively light.

Pneumatic pipe, elbows and equipment in the line are subjected to the abrasive action of the muck particles. The velocity of the air and entrained particles increases at an approximately uniform rate along the pipe due to decreasing pressure and reaches the highest velocity near the exit. Wear is associated with velocity and the resulting turbulence. Experience with pneumatic pipe indicates that by rotating pipes to distribute wear about 50,000 tons of muck can be transported through a pipe section before abandonment (69). Radmark estimates life of 100,000 tons for Esser pipe handling a mixture of shales and sandstone (67a). This is equivalent to 200,000 tons of material excavated if an extending pipeline is used since each length of pipe is in use only one-half the time. However, such pneumatic systems function at pressures of 10 psig or less, and the velocities, turbulence and wear are substantially less than for the conditions derived from the Konchesky equations. Wear in the vertical section should not be a problem because this pipe is used for a limited time only, and then grouted and abandoned after transporting less than 25,000 tons. However, the horizontal sections and the elbows will be in use until they wear out. Engineering data relating wear rates to particle velocity or air turbulence are not available at present in the velocity range indicated by the Konchesky equations, so the feasibility of using pipe for these large tonnages and high velocities is uncertain.

Although the pipe wear may be a serious problem, the wear could be more or less evenly distributed over all pipe sections by reversing the order of installation of pipe sections as the system is moved from one borehole to the next. With this arrangement, each pipe segment is in place half the time. Since each pipe section is assumed to be capable of transporting 50,000 tons, and since the muck is excavated at the rate of 25 tons per foot of tunnel length, the 1000 feet of pipe sections in the horizontal segments must be completely replaced every 4000 tunnel feet. Allowing for extra replacements, 6000 feet of pipe are planned for the near term case and 22,000 feet of pipe for the far term case. All the boreholes are prepared beforehand along the right of way, and cased to a depth short of the crown of the tunnel so the cutters will not damage the pipe. When the mole reaches and passes the position of the borehole, handwork is needed to clear away the entrance to the pipe and make room for a quick connect device. The borehole is eventually grouted and abandoned.

The air-solids separation system must be mobile so that the entire system can be moved from one borehole to the next in a period of one day. The equipment would be mounted on trailers or in vans that could be pulled by a tractor over city streets. Two major components, one to separate large particles and the other to control dust, would be needed. There are several techniques applicable to each requirement, including pneumatic cyclone, settling chamber, scrubber, and baghouse. Within the limits of this study, no design was prepared and only a cursory investigation conducted to ascertain the feasibility and relative economy of the various types of equipment. Rather than conduct a lengthy analysis to select specific types of equipment, funds for this equipment were included in the cost estimate by specifying the generic type of equipment for solids separation and dust control.

The noise from the blowers and crusher if underground will be excessive unless special precautions are taken to control the emission of sound. As a minimum, these components must be surrounded to the greatest extent possible by sound absorbing material.

SYSTEM SIZING

Pneumatic systems currently operate with thruput rates considerably less than projected for the muck rates of advanced moles. At present (1978) stowers for 300 tons per hour are in design, but none this large has been tested, so there are no experimentally proven engineering data for design at 400 or 900 tons per hour.

Two sets of equations for transport of bulk materials by pneumatic systems have been published. One set developed by Konchesky, George and Craig in 1975 (44,45) was derived by regression analysis of extensive data measured at the U.S. Bureau of Mines' Morgantown Research Center on horizontal and vertical pipelines transporting coal and rock. Among the several hundred tests reported in their papers, the highest thruput rate was 57.45 tons per hour. This rate of material, with a specific gravity of 1.42, was transported through a 6-inch pipe with a pressure of 25.3 psia and an air flow rate of 1388 actual cfm. Konchesky, George, and Craig determined the analytical form of their pneumatic pipeline equations by graphical

analysis of the data and then calculated the numerical value of the coefficients by statistical methods.

The other set of equations (including graphical representation of relationships) was developed by Professor R. A. Duckworth and presented at a short course at the University of Kentucky in June 1977. These equations and graphs with sample calculations have been published by Faddick and Martin in Section 5 of Report No. UMTA-MA-06-0025-78-4 entitled "The Transportation of Tunnel Muck by Pipeline" (28). The approach presented by Professor Duckworth has been studied by Dr. Faddick (23) and found to be theoretically sound. The approach was tested on the pneumatic pipeline prototype at the Colorado School of Mines and a satisfactory correlation obtained. Using the Duckworth relationships and the conditions of the six cases calculated by Radmark (67a), Faddick (23) calculated the overall pressure drops. The results obtained verified the validity of the Radmark values of pressure drop.

In discussing the Konchesky equations (44, 45), Faddick (23) points out that

a. the ratio of pickup area to pipe area is included as a term in the equation for horizontal flow

b. the air rate is indicated to be proportional to $D^{2.352}$ (rather than D^2) and

c. the pressure drop equation bears no resemblance to the established Darcy-Weisbach equation.

These and other considerations cast doubt on the theoretical basis for the equations used to describe the physical phenomenon even though the equations are a good representation of the measured data. Without a sound theoretical basis for scale-up, extrapolation far from the data range should be approached with caution.

To obtain a comparison of the Konchesky and Duckworth methods (represented by the Radmark design data), and the impact on system costs, the Konchesky equations were used to size the pipes and blowers for the pipe profile of Figure 30. The numerical data obtained from these calculations are contained in Table 53. The major differences in the data obtained by the two methods (comparison of Tables 53 and 71) is the much larger pipe diameter of Table 71 (20 and 30 inches vs 12 inches) and the much less power (2400 and 4800 hp vs 4060 and 11,200 hp) and pressure (11 and 12 psi vs 48 and 101 psi) of Table 71.

An estimate of the air and muck velocity near the pipe outlet was obtained by calculating the volume rate of air at standard conditions, adding the volume rate of the solids and dividing by the pipe cross-sectional area. Although this velocity will not correspond exactly to the velocity at the outlet, it provides an unambiguous criterion for selecting a pipe cross-sectional area. Figure 31 shows this velocity as a function of diameter with a thruput of 400 tons per hour. A minimum velocity is indicated for a pipe diameter of 12 inches. For this reason a 12-inch pipe was selected. A similar curve for 900 tons per hour indicates a minimum for a 13-inch pipe, so a standard 12-inch pipe also was selected for this case.

TABLE 53. PNEUMATIC TRANSPORT SYSTEM DATA

Based on extrapolation of Konchesky equations (44, 45)

			Numerical Value	
		Units	Near Term	Far Term
1	Maximum muck size	inches	18x12x8	18x12x8
2	Top particle size into crusher	inches	12	12
3	Top particle size into stower	inches	2.5	2.5
4	Muck specific gravity		2.65	2.65
5	Thruput rate	tons/hour	400	900
6	Pipe inside diameter	inches	12	12
7	Blower power (theoretical)	hp	3335	8746
8	Brake horsepower	hp	4,060	11,200
9	Horizontal transport distance (maximum)	feet	1,000	1,000
10	Vertical lift	feet	120	220
11	Pressure	psig	48.2	101.3
12	Volume of air flow at pressure	cubic feet/min	10,184	11,057
13	Velocity near nozzle (approximate)	feet/second	600	1,000
14	Pounds of muck per pound of air		6.9	7.6

TABLE 54. COST OF PNEUMATIC EQUIPMENT
(20-ft diameter tunnel)

	Near Term			Far Term		
	Unit Cost ($)	Number of Units	Cost (Thousands $)	Unit Cost ($)	Number of Units	Cost (Thousands $)
Borehole	13,153	34	447	44,711	74	3,309
Conveyor	0	0	0	300/foot	250 ft	75
Grizzly	35,000	2	70	126,200	2	252
Crusher	96,000	1	96	200,000	1	200
Stower	144,000	5	720	285,000	5	1,425
Blower & Power Pack	143,500	2	287	259,000	2	518
Drive Assembly	525,000	1	525	2,000,000	1	2,000
Telescoping Assembly	13,600	12	163	102,000	2	204
Ball Joints	4,600	12	55	5,000	14	70,000
Pipe(1) and Fittings	65/ft	1000 ft	65	76/ft	1000 ft	76
Pipe(2) and Fittings	65/ft	5000 ft	325	76/ft	21000 ft	1,596
Settling Chamber/Cyclone	100,000	1	100	150,000	1	150
Baghouse	100,000	1	100	150,000	1	150

(1) Pipe costs charged to plant and equipment cost in computer program.

(2) Pipe costs charged to operation and maintenance cost in computer program.

Tunnel length; 20,000 ft near term, 80,000 ft far term.

Average advance rate, ft/day; 120 near term, 300 far term.

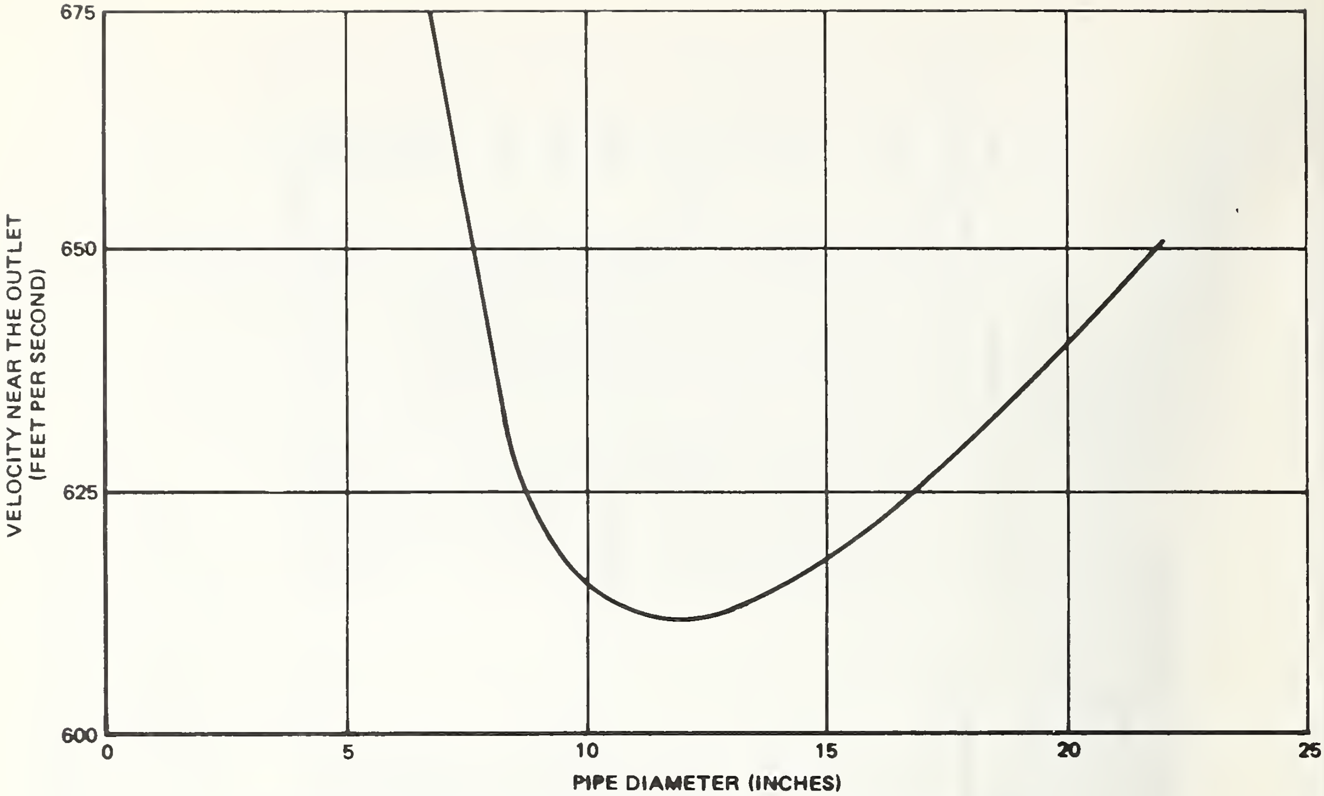


FIGURE 31. VELOCITY OF AIR AND MUCK NEAR PIPE EXIT

(Throughput 400 tons per hour; underground horizontal distance 1000 feet; lift 120 feet)

The theoretical horsepower can be converted to the horsepower input of the compressor (brake horsepower) by applying corrections for losses from various sources. The losses vary with equipment design, speed, ratio of compression and other factors. For pressures of 48.2 and 101.3 psi, the ratios of theoretical to brake horsepower are approximately 0.82 and 0.78, respectively, for the near and far term cases, giving for the brake horsepower values of 4,060 and 11,200 (Table 53). The pressures obtained are much higher than normally used for pneumatic conveying and could present problems.

The velocity of the air and the fine muck, will be in the vicinity of 600 feet per second in the near term and 1,000 feet per second in the far term cases. Velocities of these magnitudes, close to sonic velocity, would be difficult to control in the separator and present formidable problems of pipe wear. In practice pneumatic pipelines are designed with a small diameter pipe in the upstream region and a larger diameter in the downstream region, so that the air and solids flow at reasonable velocities. Procedures for matching boundary conditions in a pipeline with varying diameters has not been found in the open literature. Further, there is no adequate theoretical foundation available upon which to build a method for such calculations.

The Konchesky equations were developed empirically and do not suggest a method.

Due to the complex relationship between velocity, system loading and power input, and the lack of engineering data in the range of interest, extensive engineering and testing would be required to verify the system design.

COSTS

Equipment Costs

The major elements of the pneumatic system include conveyors, grizzlies, blowers, stower, drive assembly, telescoping assembly pipes, and the air-solids separation unit. The major equipment items, costed from data provided by Faddick and Martin (24) with a factor of 1.6 for escalation, are summarized in Table 54. The cost data provided by Radmark Engineering is given in Table 71.

The cost of pneumatic pipe is found in the cost estimate in two places. The first thousand feet of pipe and fittings are used in the initial installation and charged to the plant and equipment account. The remainder of the pipe replaces worn-out pipe sections and enters as an O&M cost.

Due to wear of the feeder tips and side-jaw liners, the feeders will function from about a week to 3 weeks before being replaced for repair. Allowing a reasonable amount of time for this repair and allowing for spare stowers, a total of up to five stowers is required to keep one in continuous operation.

Boreholes

Costs for the boreholes include drilling, lining, temporary capping, and grouting for abandonment. These costs, shown in Table 55, are engineering estimates derived from current practice in the United States.

TABLE 55. BOREHOLE COSTS
(14-inch diameter hole)

	Depth (Feet)	Inside Diameter of Pipe (Inches)	Number of Holes	Cost Per Hole (Dollars)
Near Term	100	12	34	13,153
Far Term	200	12	74	44,711

The blowers require substantial electric power, cable extensions to keep up with the advancing tunnel face and noise suppression equipment. Electric power for the blower was priced at $0.06 per horsepower-hour. The cost to

TABLE 56. WORK CREWS, PNEUMATIC SYSTEM

	Rate per Shift (Dollars/Shift)		Number of Men on Daily Shifts		Number of Men on Saturday		Remove Fan Line and Hydraulics	
	Near Term	Far Term	Near Term	Far Term	Near Term	Far Term	Near Term	Far Term
Materials Handling Supervisor	114	114	1.5	1.5				
Bull Gang Laborer	107	107	0.5	0.5				
Motorman	139	139	1.0	1.0	1.0	1.0		
Mechanic	107	107	1.0	1.0	1.0	1.0		
Bottomman	114	114	1.0	3.0	1.0	1.0		
Pneumatic Supervisor	114	148	3.0	3.0				
Crusher Operator	143	148	3.0	3.0			2.0	2.0
Stower Operator	139/143	148	3.0	3.0	1.0	1.0	2.0	
Pipe Handlers	107	115	4.5	4.5	2.0	4.0	4.5	4.5
Blower Operator	143	148	3.0	3.0			2.0	
Yard Crane Operators/Oilers	115	115	1.0	1.0	2.0	2.0	3.0	3.0
Labor Foreman	88	88	1.0	1.0			3.0	3.0
Laborers/Truck Driver	84	84	1.0	1.0	1.0	2.0	6.0	6.0
Separator Operator	115	119	3.0	3.0	1.0	1.0		
Dust Control Operator	115	119	3.0	3.0	1.0	1.0		
Truck Driver	75	75	1.0		1.0	1.0		
Mechanic	111/147	111/147			.5	1.5		
Shifter	135	135					9.0	9.0
Miners	123	123					18.0	18.0
Chucktenders	114	114					9.0	9.0

TABLE 57. MOLING AND DELAY TIMES

(Pneumatic System)

Item	Time (Hours)	
	Near Term	Far Term
Moling	1944	3278
Reset	108	221
Rock Support, Bolts	0	0
Sets	400	427
Materials Handling, Derail	10	16
Connect Vertical Shaft	24	0
Pipe Extensions	167	199
Reset Conveyors	0	0
Pump Line	0	0
Ventilation	39	79
Power, Add Cable	54	78
Outages	16	24
Cutters	97	159
Repairs, Mole	389	636
Material Handling	194	286
Drills	58	95
Other	19	32
Shift Change	156	238
Miscellaneous	456	480
Total Time	4,131	6,148
Total Time (Days)	172	256

purchase and install the electrical components to supply the blower was scaled up from the cost of the utilities for the base case, based upon the ratio of blower horsepower to mole horsepower.

Personnel Costs

A set of job titles for the personnel operating the pneumatic system was prepared, the job compared with existing jobs, and wages assigned on the basis of similarity. Table 56 lists the jobs by title, the rate per shift, the number of personnel assigned per shift and assigned to Saturday maintenance, and the number of personnel needed to remove the fan line and pneumatic lines.

MOLING TIME AND JOB DURATION

The moling time for the pneumatic system is assumed to be the same as for the hydraulic system. The estimated hours lost due to delays differ somewhat for the two systems as seen by comparing Table 49 with Table 57, which contains data relevant to delays and total scheduled hours for the pneumatic system.

COMPUTER COSTING

The elements of data for costing the job with a computer program are discussed in Appendix B. The major elements developed by the methods indicated were entered into the computer, which produced the cost breakdowns for the near and far term cases as summarized in Tables 58 through 61. The costs per tunnel foot for the near and far term pneumatic cases are $576 and $391 per tunnel foot, respectively, using the Konchesky approach, and $559 and $393, respectively, using the Radmark data. This close agreement is the result of decreases in some cost elements, but increases in others.

CONVEYOR-PNEUMATIC SYSTEM

Another potential application of pneumatic lifting would be in combination with a conveyor for horizontal muck transport. In this hybrid system the muck would be transported by extensible conveyor from the mole to the feed preparation equipment for the pneumatic system and then lifted vertically in a pipe within a borehole to the surface for eventual disposal.

Since it is envisioned that the conveyor will be reset to a new borehole once a week as a part of Saturday maintenance, the conveyor maximum length was set equal to the maximum weekly advance distances of 1200 and 3000 feet (Section 13) for the near and far term cases. One major problem associated with conveyors is a means for negotiating curves in the tunnel. In the near term case, two separate conveyor types are needed; one type for the straight section and another for the curved parts of the tunnel. The conveyor for the straight section trails behind the mole supported on either wall brackets or monorail. On Mondays the crusher and stower are in place near the mole and the conveyor trails to the rear. A tripper feeds the muck from the extensible conveyor onto a fixed conveyor leading to a chute. As the mole advances, it drags the conveyor forward. The tripper and loading systems remain stationary. By Friday, the mole has advanced and dragged the

TABLE 58. COST ESTIMATE, PNEUMATIC, NEAR TERM

31 NEAR TERM PNEUMATIC — ESTIMATOR LAG — DATE 10/07/77

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	1271535.			722871.		
EQUIPMENT REPAIR LABOR	176177.			159544.		
EQUIPMENT PARTS AND SUPPLIES	544397.			496670.		
SUPPLIES	928634.			44121.		
MATERIAL	898700.			0.		
SUBCONTRACTS	33000.			1125787.		
TOTAL DIRECT COST			3852443.			2548993.
PLANT AND EQUIPMENT						
PURCHASE COST	3795300.			3944825.		
SALVAGE	2733285.			2740083.		
NET COST		1062015.			1204742.	
RENT	3000.			10000.		
FREIGHT IN AND OUT	101000.			123000.		
ERECTION AND REMOVAL	316000.			125000.		
SUBTOTAL OTHER THAN PURCHASE		420000.			258000.	
TOTAL PLANT AND EQUIPMENT			1482015.			1462742.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			5334458.			4011735.
INDIRECT COST						
OVERHEAD LABOR	933792.			0.		
MISCELLANEOUS JOB EXPENSE	356500.			0.		
INSURANCE AND TAXES	598251.			276368.		
TOTAL INDIRECT COST			1888543.			276368.
TOTAL		63. PERCENT	7223000.		37. PERCENT	4288102.
TOTAL JOB COST						11511103.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						576.

31 NEAR TERM PNEUMATIC — SUMMARY (DOLLARS) — PAGE 1

TABLE 59. COST ESTIMATE, PNEUMATIC, NEAR TERM

N T PNEUMATIC/RADMARK COSTS — ESTIMATOR LAG — DATE 08/18/78

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	1271535.			640109.		
EQUIPMENT REPAIR LABOR	176177.			159544.		
EQUIPMENT PARTS AND SUPPLIES	544397.			601642.		
SUPPLIES	928634.			39983.		
MATERIAL	898700.			0.		
SUBCONTRACTS	33000.			1125787.		
TOTAL DIRECT COST			3852443.			2567064.
PLANT AND EQUIPMENT						
PURCHASE COST	3795300.			2364295.		
SALVAGE	2733285.			1451333.		
NET COST		1062015.			912962.	
RENT	3000.			10000.		
FREIGHT IN AND OUT	101000.			163000.		
ERECTION AND REMOVAL	316000.			115000.		
SUBTOTAL OTHER THAN PURCHASE		420000.			288000.	
TOTAL PLANT AND EQUIPMENT			1482015.			1200962.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			5334458.			3768026.
INDIRECT COST						
OVERHEAD LABOR	933792.			0.		
MISCELLANEOUS JOB EXPENSE	356500.			0.		
INSURANCE AND TAXES	598251.			180563.		
TOTAL INDIRECT COST			1888543.			180563.
TOTAL		65. PERCENT	7223000.		35. PERCENT	3948589.
TOTAL JOB COST						11171589.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						559.

N T PNEUMATIC/RADMARK COSTS — SUMMARY (DOLLARS) — PAGE 1

TABLE 60. COST ESTIMATE, PNEUMATIC, FAR TERM

TABLE 60. COST ESTIMATE, PNEUMATIC, FAR TERM

30 FAR TERM PNEUMATIC ESTIMATOR LAG DATE 11/07/77

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	2249376.			1158010.		
EQUIPMENT REPAIR LABOR	307606.			235212.		
EQUIPMENT PARTS AND SUPPLIES	2124204.			2200285.		
SUPPLIES	2863535.			69661.		
MATERIAL	3594800.			0.		
SUBCONTRACTS	33000.			6081592.		
TOTAL DIRECT COST			11172521.			9744760.
PLANT AND EQUIPMENT						
PURCHASE COST	6884750.			8604880.		
SALVAGE	4256465.			5882350.		
NET COST		2628285.			2722530.	
RENT	3000.			20000.		
FREIGHT IN AND OUT	170000.			270000.		
ERECTION AND REMOVAL	399000.			118000.		
SUBTOTAL OTHER THAN PURCHASE		572000.			408000.	
TOTAL PLANT AND EQUIPMENT			3200285.			3130530.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			14372806.			12875290.
INDIRECT COST						
OVERHEAD LABOR	1253734.			0.		
MISCELLANEOUS JOB EXPENSE	532080.			0.		
INSURANCE AND TAXES	1294674.			654596.		
TOTAL INDIRECT COST			3080488.			654596.
TOTAL		56. PERCENT	17453293.		44. PERCENT	13529885.
TOTAL JOB COST						30983178.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						387.

30 FAR TERM PNEUMATIC SUMMARY (DOLLARS) PAGE 1

TABLE 61. COST ESTIMATE, PNEUMATIC, FAR TERM

(Radmark Data)

F T PNEUMATIC/RADMARK COST — ESTIMATOR LAG — DATE 08/18/78

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	2249376.			1032819.		
EQUIPMENT REPAIR LABOR	307606.			235212.		
EQUIPMENT PARTS AND SUPPLIES	2124204.			3965917.		
SUPPLIES	2863535.			63402.		
MATERIAL	3594800.			0.		
SUBCONTRACTS	33000.			6081592.		
TOTAL DIRECT COST			11172521.			11378942.
PLANT AND EQUIPMENT						
PURCHASE COST	6884750.			4245030.		
SALVAGE	4256465.			2531000.		
NET COST		2628285.			1714030.	
RENT	3000.			20000.		
FREIGHT IN AND OUT	170000.			319000.		
ERECTION AND REMOVAL	399000.			126000.		
SUBTOTAL OTHER THAN PURCHASE		572000.			465000.	
TOTAL PLANT AND EQUIPMENT			3200285.			2179030.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			14372806.			13557972.
INDIRECT COST						
OVERHEAD LABOR	1253734.			0.		
MISCELLANEOUS JOB EXPENSE	532080.			0.		
INSURANCE AND TAXES	1294674.			467038.		
TOTAL INDIRECT COST			3080488.			467038.
TOTAL		55. PERCENT	17453293.		45. PERCENT	14025010.
TOTAL JOB COST						31478302.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						393.

F T PNEUMATIC/RADMARK COST — SUMMARY (DOLLARS) — PAGE 1

extensible conveyor forward so that the tripper is located at some intermediate point along the conveyor. On the weekend, the tripper, fixed conveyors, chutes, loader and other pieces of equipment are moved forward to the next borehole. During the week, the wall brackets or monorail must be extended to keep pace with the mole.

It is projected that the extensible conveyor, which will be available in the near term time period, will perform satisfactorily only in the straight sections of the tunnel. In the curved portions a set of 12 conveyor units, each 100 feet in length, will carry the muck around the curve.

The installation and maintenance of the monorail sections or the 100-foot sections will require the services of the equivalent of one man working three shifts per day.

It is reasonable to assume that, with the projected advances in the state of the art, a flexible conveyor mounted on a monorail with the capability of functioning in both the curved and straight sections of the tunnel will be available in the far term time period. The tripper, fixed conveyor, and pneumatic system in the far term case will function in a manner similar to that described for the near term case. The installation and maintenance of the monorail will require the services of three men on each work shift.

The pneumatic portion of the system was sized with the Konchesky equations and by Radmark Engineering for the profile shown in Figure 32. In the tunnel, a 50-foot horizontal pipe section provides a length for acceleration before entering an elbow to the straight lifting section. The muck is transported vertically to a point 20 feet above the ground, then through another elbow into a 30-foot straight section leading to the muck-air separator.

Table 62 summarizes the numerical values (calculated by the Konchesky equations) of the major parameters for the pneumatic lift system and compares them to the values for the pneumatic horizontal transport and lift system. Note that the air flow rate and power are similar for three of the cases, but significantly less for the near term pneumatic lifting case. This difference can be traced to the smaller diameter pipe (10-inch) that can be used in this case. If a 12-inch pipe had been selected here, an air volume rate of 10,051 cfm and theoretical power of 1075 hp would have been required, values more in line with the other cases.

Values calculated by Radmark Engineering for lifting only are given in Table 71, cases 5 and 6.

<u>Costs</u>

The costing procedure used for the pneumatic lifting system is similar to that used for the pneumatic system discussed previously. Table 63 summarizes the equipment costs as based largely upon the costing data provided by Faddick and Martin (24). Costs provided by Radmark Engineering are given in Table 71.

TABLE 62. COMPARISON OF PNEUMATIC SYSTEMS

(Calculated values based on Konchesky equations)

	Item	Units	Near Term		Far Term	
			Transport and Lift	Lift Only	Transport and Lift	Lift Only
1	Maximum Mole Muck Size	inches	18x12x8	18x12x8	18x12x8	18x12x8
2	Top Partial Size into Crusher	inches	12	12	12	12
3	Top Partial Size into Stower	inches	2.5	2.5	2.5	2.5
4	Muck Specific Gravity		2.65	2.65	2.65	2.65
5	Thruput Rate	tons/hour	400	400	900	900
6	Pipe Inside Diameter	inches	12	10	12	12
7	Blower Power (Theoretical hp)	horsepower	3,335	788	8,746	3,740
8	Brake Horsepower	horsepower	4,075	960	11,200	4,800
9	Horizontal Transport Distance (Maximum)	feet	1,000	37	1,000	37
10	Vertical Lift	feet	120	120	220	220
11	Pressure	psig	48.2	20.9	101.3	51.2
12	Volume of Air Flow at Pressure	cubic feet/min	10,184	6,490	11,057	10,660
13	Velocity Near Nozzle (Approximate)	feet/second	600	375	1,000	600
14	Pounds of Muck per Pounds of Air		6.9	10	7.6	31
15	Horizontal Distance	feet	1,000	36.5	1,000	36.5
16	Vertical Distance	feet	120	120	220	220

TABLE 63. CONVEYOR-PNEUMATIC SYSTEM EQUIPMENT COST

Item	Near Term			Far Term		
	Unit Cost ($)	Number of Units	Cost (Thousands $)	Unit Cost (Dollars)	Number of Units	Cost (Thousands $)
Boreholes	13,152	34	447	44,711	74	3,309
Conveyors	500	1,200	600	500	3,000	1,500
Conveyors	100	4	-	300	250	75
Grizzly and Screens	35,000	2	70	126,200	2	252
Crusher	96,000	1	96	200,000	1	200
Stower	144,000	5	720	285,600	5	1,428
Blower	115,000	2	230	259,000	2	518
Drive Assembly	89,000	1	89	400,000	1	400
Pipe per Foot	55	700	39	65	1,500	98
Power Pack	57,000	1	57	*	*	*
Settling Chamber, Cyclone	100,000	1	100	150,000	1	150
Baghouse	100,000	1	100	150,000	1	150
Total Cost			2,101			4,771

*Included in Drive Assembly Costs.

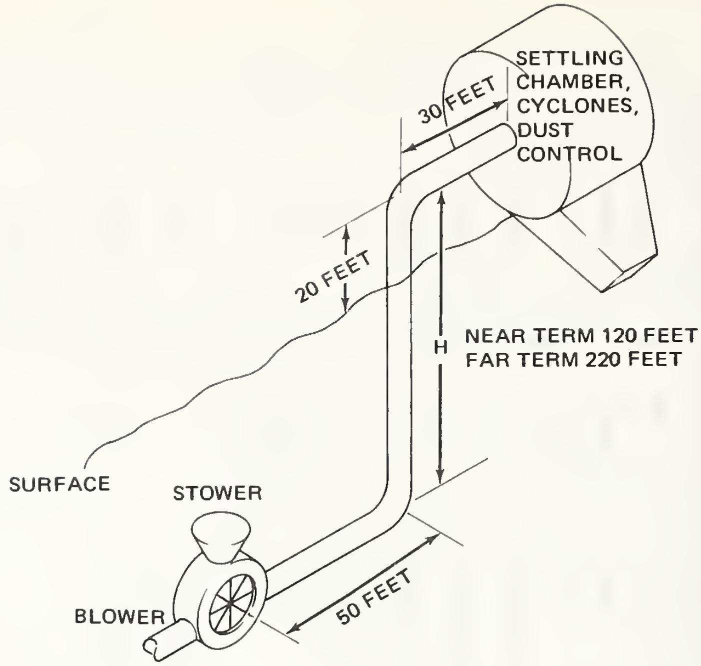


FIGURE 32. PNEUMATIC LIFT SYSTEM PROFILE

The cost of the near term conveyor system contains funds for the conveyor section used in the straight parts of the tunnel, the 12 units of 100 feet length each for the curved parts, a small fixed conveyor and a chute. The conveyor for the straight section is costed at $300 per foot including brackets to be mounted on the wall. The 100-foot units were costed at $150 per foot. Adding the costs for the chutes, fixed conveyors, and fixtures, brings the average cost of the combined system to $500 per foot. Estimates for equipment and other materials for the far term flexible conveyor also came to $500 per foot.

Moling Time and Job Duration

The moling time, delay times, and total job duration for the conveyor-pneumatic systems are assumed to be the same as for the pneumatic system summarized in Table 57.

Computer Costing

The computer costing for this system was conducted in a manner similar to that for the other systems. The summary sheets are displayed in Tables 64 through 67. The costs per tunnel foot are $541 and $357 for the near and far term cases based on the Konchesky equations, and $536 and $361, respectively, based on the Radmark Engineering data. The close agreement is the result of cost decreases in some cost elements being offset by increases in other cost elements.

TABLE 64. COST ESTIMATE, CONVEYOR-PNEUMATIC, NEAR TERM

33 NT PNEUMATIC W CONVEYOR ESTIMATOR LAG DATE 10/21/77

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	1271535.			805634.		
EQUIPMENT REPAIR LABOR	176177.			168969.		
EQUIPMENT PARTS AND SUPPLIES	544397.			165777.		
SUPPLIES	928634.			48730.		
MATERIAL	898700.			0.		
SUBCONTRACTS	33000.			1125787.		
TOTAL DIRECT COST			3852443.			2314897.
PLANT AND EQUIPMENT						
PURCHASE COST	3795300.			2799645.		
SALVAGE	2733285.			1901283.		
NET COST		1062015.			898362.	
RENT	3000.			10000.		
FREIGHT IN AND OUT	101000.			99000.		
ERECTION AND REMOVAL	316000.			97000.		
SUBTOTAL OTHER THAN PURCHASE		420000.			206000.	
TOTAL PLANT AND EQUIPMENT			1482015.			1104362.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			5334458.			3419259.
INDIRECT COST						
OVERHEAD LABOR	933792.			0.		
MISCELLANEOUS JOB EXPENSE	356500.			0.		
INSURANCE AND TAXES	598251.			187415.		
TOTAL INDIRECT COST			1888543.			187415.
TOTAL		67. PERCENT	7223000.		33. PERCENT	3606674.
TOTAL JOB COST						10829674.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						541.

TABLE 65. COST ESTIMATE CONVEYOR-PNEUMATIC, NEAR TERM (Radmark Data)

NT CONVEYOR/PNEU/RADMARK ESTIMATOR JMD DATE 08/25/78

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	1271535.			805634.		
EQUIPMENT REPAIR LABOR	176177.			168969.		
EQUIPMENT PARTS AND SUPPLIES	544397.			98345.		
SUPPLIES	928634.			48730.		
MATERIAL	898700.			0.		
SUBCONTRACTS	33000.			1125787.		
TOTAL DIRECT COST			3852443.			2247465.
PLANT AND EQUIPMENT						
PURCHASE COST	3795300.			2662745.		
SALVAGE	2733285.			1756283.		
NET COST		1062015.			906462.	
RENT	3000.			10000.		
FREIGHT IN AND OUT	101000.			111000.		
ERECTION AND REMOVAL	316000.			106000.		
SUBTOTAL OTHER THAN PURCHASE		420000.			227000.	
TOTAL PLANT AND EQUIPMENT			1482015.			1133462.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			5334458.			3380927.
INDIRECT COST						
OVERHEAD LABOR	933792.			0.		
MISCELLANEOUS JOB EXPENSE	356500.			0.		
INSURANCE AND TAXES	598251.			175084.		
TOTAL INDIRECT COST			1888543.			175084.
TOTAL		67. PERCENT	7223000.		33. PERCENT	3556011.
TOTAL JOB COST						10779011.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						539.

TABLE 66. COST ESTIMATE, CONVEYOR-PNEUMATIC, FAR TERM

34 FT PNEUMATIC W CONVEYOR ESTIMATOR LAG DATE 10/21/77

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	2249376.			1278971.		
EQUIPMENT REPAIR LABOR	307606.			256821.		
EQUIPMENT PARTS AND SUPPLIES	2124204.			524525.		
SUPPLIES	2863535.			76790.		
MATERIAL	3594800.			0.		
SUBCONTRACTS	33000.			6081592.		
TOTAL DIRECT COST			11172521.			8218698.
PLANT AND EQUIPMENT						
PURCHASE COST	6884750.			6505380.		
SALVAGE	4256465.			4499200.		
NET COST		2628285.			2006180.	
RENT	3000.			20000.		
FREIGHT IN AND OUT	170000.			269000.		
ERECTION AND REMOVAL	399000.			142000.		
SUBTOTAL OTHER THAN PURCHASE		572000.			431000.	
TOTAL PLANT AND EQUIPMENT			3200285.			2437180.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			14372806.			10655878.
INDIRECT COST						
OVERHEAD LABOR	1253734.			0.		
MISCELLANEOUS JOB EXPENSE	532080.			0.		
INSURANCE AND TAXES	1294674.			440319.		
TOTAL INDIRECT COST			3080488.			440319.
TOTAL		61. PERCENT	17453293.		59. PERCENT	11096197.
TOTAL JOB COST						28549490.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						357.

34 FT PNEUMATIC W CONVEYOR SUMMARY (DOLLARS) PAGE 1

TABLE 67. COST ESTIMATE CONVEYOR-PNEUMATIC, FAR TERM

FT CONVEYOR/PNEU/RADMARK ESTIMATOR ~~[illegible]~~ JMD DATE [illegible]

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	2249376.			1278971.		
EQUIPMENT REPAIR LABOR	307606.			256821.		
EQUIPMENT PARTS AND SUPPLIES	2124204.			362330.		
SUPPLIES	2863535.			76790.		
MATERIAL	3594800.			0.		
SUBCONTRACTS	33000.			6081592.		
TOTAL DIRECT COST			11172521.			8056503.
PLANT AND EQUIPMENT						
PURCHASE COST	6884750.			6584880.		
SALVAGE	4256465.			4174200.		
NET COST		2628285.			2410680.	
RENT	3000.			20000.		
FREIGHT IN AND OUT	170000.			324000.		
ERECTION AND REMOVAL	399000.			142000.		
SUBTOTAL OTHER THAN PURCHASE		572000.			486000.	
TOTAL PLANT AND EQUIPMENT			3200285.			2896680.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			14372806.			10953183.
INDIRECT COST						
OVERHEAD LABOR	1253734.			0.		
MISCELLANEOUS JOB EXPENSE	532080.			0.		
INSURANCE AND TAXES	1294674.			434343.		
TOTAL INDIRECT COST			3080488.			434343.
TOTAL		61. PERCENT	17453293.		39. PERCENT	11387526.
TOTAL JOB COST						28840819.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						361.

FT CONVEYOR/PNEU/RADMARK SUMMARY (DOLLARS) PAGE 1

RAIL - PNEUMATIC SYSTEM

Computer cost estimates were made for material handling systems using rail for horizontal transport and pneumatic conveying for lifting muck to the surface. Costs were obtained for these systems by substituting pneumatic lift systems for the crane or hoist of the base cases. Only cost estimates based on data provided by Radmark Engineering (Table 71, cases 5 and 6) were made for rail-pneumatic systems.

The computer summary sheets are displayed in Tables 68 and 69. The costs per tunnel foot are \$559 and \$342 for the near and far term cases, respectively.

RADMARK DESIGN AND COSTS

The following discussion and data are provided by Radmark Engineering, Inc. (67a).

System Design Calculations

The calculations to determine the air volume and operating pressure requirements for each of the six cases, are obtained from a computer program based on proprietary information. When these have been calculated, the blower capacity, pipeline diameter and selection of rotating air lock feeder are determine. Although the results are for hypothetical study only, the same care has been taken in selecting the equipment as if these were to be included in a commercial quotation for which a Radmark written guarantee is provided.

The following information forms the basis of each calculation:

1. Maximum particle size of 2" at 165 lbs/cubic ft

2. Average particle thickness .37"

3. Elevation at sea level

4. Inlet and discharge silencers fitted to the blower

5. Expanding air line where required

6. Discharge to cyclone

Cases 5 and 6 are for lifting only with system capacities of 400 tph and 900 tph respectively. Cases 1 through 4 are for 1000 feet of underground horizontal transport and lifting to the surface for system capacities of 50 tph, 100 tph, 400 tph and 900 tph respectively.

Equipment Selection and Costs

The component parts that make up the pneumatic systems proposed for each of the six cases are based on units that are commercially available. No

TABLE 68. COST ESTIMATE, RAIL-PNEUMATIC, NEAR TERM

N T RAIL/PNEU/RADMARK COST   ESTIMATOR LAG   DATE 08/18/78

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	1228392.			858111.		
EQUIPMENT REPAIR LABOR	163792.			360036.		
EQUIPMENT PARTS AND SUPPLIES	533248.			553219.		
SUPPLIES	919749.			60907.		
MATERIAL	898700.			0.		
SUBCONTRACTS	33000.			691738.		
TOTAL DIRECT COST			3776882.			2524011.
PLANT AND EQUIPMENT						
PURCHASE COST	3795300.			2944000 ~~3417150.~~		
SALVAGE	2733285.			2106000 2460847.		
NET COST		1062015.			838000 ~~956303.~~	
RENT	3000.			34000.		
FREIGHT IN AND OUT	101000.			189,000 ~~195000.~~		
ERECTION AND REMOVAL	316000.			201,000 ~~208000.~~		
SUBTOTAL OTHER THAN PURCHASE		420000.			424000 ~~437000.~~	
TOTAL PLANT AND EQUIPMENT			1482015.			1262000 ~~1393303.~~
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			5258897.			3786011 ~~3917313.~~
INDIRECT COST						
OVERHEAD LABOR	933792.			0.		
MISCELLANEOUS JOB EXPENSE	356500.			0.		
INSURANCE AND TAXES	597249.			249249.		
TOTAL INDIRECT COST			1887541.			249249.
TOTAL		63. PERCENT	7146438.		37. PERCENT	4035260 ~~4166502.~~
TOTAL JOB COST						11181698 ~~11313000.~~
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						~~565.~~ 559

N T RAIL/PNEU/RADMARK COST   SUMMARY (DOLLARS)   PAGE 1

TABLE 69. COST ESTIMATE, RAIL-PNEUMATIC, FAR TERM

(Radmark Data)

L T RAIL/PNEU/RADMARK COST ESTIMATOR LAG DATE 08/18/78

	OTHER THAN MATERIALS HANDLING			MATERIALS HANDLING		
DIRECT COST						
LABOR	2214345.			1392579.		
EQUIPMENT REPAIR LABOR	304282.			545485.		
EQUIPMENT PARTS AND SUPPLIES	2097271.			2322531.		
SUPPLIES	2857398.			96903.		
MATERIAL	3594800.			0.		
SUBCONTRACTS	33000.			2816372.		
TOTAL DIRECT COST			11101097.			7173871.
PLANT AND EQUIPMENT						
PURCHASE COST	6884750.			5566900.		
SALVAGE	4256465.			3862040.		
NET COST		2628285.			1704860.	
RENT	3000.			44000.		
FREIGHT IN AND OUT	170000.			359000.		
ERECTION AND REMOVAL	399000.			233000.		
SUBTOTAL OTHER THAN PURCHASE		572000.			636000.	
TOTAL PLANT AND EQUIPMENT			3200285.			2340860.
TOTAL DIRECT COST AND PLANT AND EQUIPMENT			14301382.			9514731.
INDIRECT COST						
OVERHEAD LABOR	1253734.			0.		
MISCELLANEOUS JOB EXPENSE	532080.			0.		
INSURANCE AND TAXES	1293020.			473634.		
TOTAL INDIRECT COST			3078834.			473634.
TOTAL		64. PERCENT	17380216.		36. PERCENT	9988364.
TOTAL JOB COST						27368581.
COST PER FOOT OF TUNNEL (EXCAVATION AND SUPPORT)						342.

L T RAIL/PNEU/RADMARK COST SUMMARY (DOLLARS) PAGE 1

items which would have to be especially designed, or for which no previous experience has been gained have been included. The pipelines, rotating air lock feeders and blowers are currently in use in pneumatic conveying systems handling large abrasive rocks, ore and coal. Costs quoted are present day costs, FOB Portland, Oregon.

Blowers - Low pressure air is supplied by Roots type blowers powered by electric motors. For the air requirements in Cases 3, 4, 5, and 6, the blowers will have to be coupled in parallel as there is no one blower available to supply the quantity of air required. Blowers are located on the surface.

Each blower assembly will consist of the components indicated with costs given in Table 70.

TABLE 70. BLOWER ASSEMBLY COMPONENT COSTS
Source: Radmark Engineering, Inc. (67a)

Component	Case		
	1	2	3,4,5, & 6
Peabody-Holmes Roots type blower Model 71 HR 80	22,000	22,000	22,000
Electric motor, 1760 rpm, 4160V 3ph 60 Hz ODP	(550hp) 10,200	(700hp) 14,000	(800hp) 15,500
Motor starter 5000V Airbreak contactor with primary fusible disconnect	5,000	5,500	6,000
Gear reducer 1.86/1 ratio, complete with couplings	3,800	4,300	4,300
Base to accommodate blower, motor and gear reducer, fabricated from steel sections	3,200	3,200	3,200
Inlet silencer & filter	4,000	4,500	5,000
Discharge silencer	5,000	5,500	6,000
Total Cost of Blower Assembly (1978 dollars)	53,200	59,000	62,000

Feeders - The material is introduced into the pipeline with a Radmark rotating airlock feeder. These units are manufactured from abrasion resistant steels, have adjustable sidejaws and pressurized end housings. The jaw liners and rotor tips are replaceable. The rotor is powered by a hydraulic motor, instantly reversible. The whole unit is mounted on a skid base for towing by the tunneling machine, with the bottom flanges contoured to suit the tunnel diameter. Various sizes of Radmark feeders are available.

Power Pack - Hydraulic power for the feeder motor is supplied from a power pack. The hydraulic pump, electric motor, tank and necessary directional and relief valves are mounted on a skid base, either attached to, or integral with, the Radmark feeder skid base. A control console with motor starter, pressure gauges, pressure sensing switches and forward-off-reverse control is mounted over the power pack. The size of power pack is related to the feeder size.

Material Conveying Pipeline (Esser Duplex) - The material conveying pipeline is manufactured from two steel plates, rolled and welded longitudinally. The inner surface is hardened following fabrication, to a hardness of 650-700 Brinell. The pipe size is selected according to the quantity of material and air volume to be handled. Individual pipe lengths of from 11 to 25 feet are available, the lengths depending on several factors such as room for handling within the tunnel, weight, and advance required before closing down the system to extend. Telescopic pipe sections, manufactured from two pipe sections with a sealing gland, allow the feeder assembly to move forward continuously. When fully extended, the outbye flange of the telescope is uncoupled, the telescope retracted and an additional pipe length inserted.

Elbows are supplied in 15-degree segments with replaceable steel liners. Two are required for each system, from the tunnel to the shaft and on the surface from the shaft to the discharge cyclone.

Air Conveying Pipeline - It is assumed that the blower will be located on the surface, and the pressurized air conducted from there to the Radmark feeder in light section steel pipes. A telescope is also required in this line. The elbows are fabricated and have mounting brackets.

Cyclone - To control dust and noise at the delivery of the conveying pipeline, the material is directed into a cyclone. These units are fitted with replaceable steel liner plates and supported on a steel framework for direct discharge into trucks.

Systems Costs - The capital costs and system descriptions for the six cases estimated are summarized in Table 71. The estimated life of system components (useful in estimating salvage values) is given in Table 72.

Operating Costs

The major operating costs are for personnel, power and replacement of equipment components and parts. Estimated frequency of replacement and cost per replacement for components and parts are indicated in Table 73.

Personnel - Regardless of the size of the pneumatic conveying system, only one operator is required to run the feeder. His main duties include the reporting of any mechanical defect or extraneous noise to the maintenance people, the reversal of the feeder should an oversize rock jam the rotor, and periodic checking of the operating pressure to ensure the system is not overloading. An operator can be trained within one week, and this is classified as a semi-skilled occupation.

TABLE 71. CAPITAL COST OF PNEUMATIC SYSTEMS

Costs in thousands of 1978 dollars
Source: Radmark Engineering, Inc. (67a)

Item	Case 1		Case 2		Case 3		Case 4		Case 5		Case 6	
	Description	Cost	Description	Cost	Description	Cost	Description	Cost	Description	Cost	Description	Cost
1 System Capacity, tph	50		100		400		900		400		900	
2 Lift Distance, ft	120		120		120		220		120		220	
3 Horizontal Distance Underground, ft	1,000		1,000		1,000		1,000		50		50	
4 Horizontal Distance on Surface, ft	30		30		30		30		30		30	
5 Free Air, cfm	6,920		8,418		28,316		61,570		26,848		61,392	
6 Net Pressure, psi	11.45		13.86		11.29		12.21		4.61		5.87	
7 Blowers, Peabody-Holmes Roots type, model 71HR80	1 @ 550hp	53.2	1 @ 700hp	59.0	3 @ 800hp ea.	186.0	6 @ 800hp ea.	372.0	3 @ 800hp ea.	186.0	6 @ 800hp ea.	372.0
8 Feeder, Radmark model RTL	RTL 100	27.6	RTL 200	47.0	RTL 600	86.0	RTL 1200	125.0	RTL 600	86.0	RTL 1200	125.0
9 Power Pack, Radmark type	100	11.5	200	12.9	600	25.5	1200	35.5	600	25.5	1200	35.5
10 Esser Pipe (length, i.d.)	1150',10"	59.6	1150',10"	59.6	1150',20"	195.5	1250',30"	275.0	200',20"	34.0	300',30"	95.1
11 Esser 90-deg. Elbows, two	10"	6.4	10"	6.4	20"	15.6	30"	23.2	20"	15.6	30"	23.2
12 Steel Pipe (length, i.d.)	1200',12"	36.0	1200',12"	36.0	1200',24"	72.0	1300',36"	117.0	250',24"	15.0	350',36"	31.5
13 Steel 90-deg. Elbows, two	12"	1.0	12"	1.0	24"	1.5	36"	2.0	24"	1.5	36"	2.0
14 Cyclone, Radmark	84"	12.3	84"	12.3	200"	28.3	400"	54.6	200"	28.3	400"	54.6
15 Total Cost, K $		207.6		234.2		610.4		1004.3		391.9		738.8
16 Total Cost $/tph		4151		2342		1526		1116		980		821

TABLE 72. ESTIMATED LIFE FOR PNEUMATIC SYSTEM COMPONENTS

Item	Life	Conditions
	years	
Blower	20	Intake filters kept in good condition. Intake air is clean, dust free.
Power Pack	10	Oil, oil filters and seals on pump unit changed at regular intervals.
Feeder	10	Replace wear items as required.
Cyclone	20	Liners replaced as required.
Esser Duplex Pipe	tons	Life depends on tons conveyed, abrasiveness and type of rock, and location in pipeline. Tonnage given for horizontal pipe rotated 120 degrees, every month. Vertical pipe life is 5-8 times that of horizontal pipe.
Coal, Shale, Mudstone	120,000	
Sandstone	80,000	
Very Abrasive Rock	50,000	

TABLE 73. PARTS REPLACEMENT COST FOR PNEUMATIC SYSTEM
(Material: Mixture of Shales & Sandstone)

Item	Cost per Replacement		Replacement Frequency (tons excav.)
Feeder			
Replace rotor tips, side-jaws liners and packing; grease and reassemble	$12,000		60,000
Replace injector tee, infeed chute, pipe connections	$ 8,000		120,000
Cyclone			
Replace tiles in high wear area	$ 200		20,000
Esser Elbows			
Replace backing tiles in high wear area	$ 150		20,000
Esser Duplex Pipe	in i.d.	$/ft	
(Horizontal pipe with flanges in extending system)	10	52	200,000
	20	170	200,000
	30	220	200,000
(heavy wall)	30	317	200,000

An operator is not normally required to oversee the blowers, but in the larger systems, with three and six blowers in parallel, it may be advisable.

Maintenance of the feeder is undertaken by a mechanic for approximately one hour each shift. He checks the gap between the rotor tips and the jaws, and if necessary adjusts the latter to reduce air blowback. The packing is also checked for leakage. Unless there are adjustments to be made, it is not necessary for the system to be stopped during the whole hour of the inspection. In fact, it is more advantageous to have the system operating.

The addition of pipes into the air and material conveying pipelines is undertaken by two men (assuming lifting tackle is available to lower the pipes into place when the telescope has been retracted). The feeder operator and one other can perform this task. Previous experience indicates that it takes approximately 12 minutes to extend both pipelines, using quick release clamps of Radmark design.

Power - The power cost for operating each system will depend on the unit cost for electric power at the tunnel site, maximum demand penalties, etc. The horsepower of each blower has been given, from which can be calculated the power consumption. It must be remembered however, that only when the system is operating at the final length, and handling the designed throughput at this length, will there be a full power demand for the blower motors.

The power pack electric motors will be near fully loaded when the feeders are running.

15. COMPARISON OF SYSTEMS

Cost estimates were made for tunneling jobs employing eleven different material handling systems for muck transport. For each material handling system, a job estimate was developed for conditions defined for the near term (1980-1990) time period and for the far term (1990+) time period. Thus, twenty-two cases were evaluated with variation of job size (20,000 and 80,000 tunnel feet), tunnel reach (10,000 and 40,000 feet), mole penetration rate (3 and 7 inches per minute, maximum), daily average advance rate (120 and 300 feet per day), underground horizontal muck transport method, and method of muck lifting from the tunnel to the surface. In addition two different sources were used to derive input design and cost data for pneumatic transport. In all cases where a continuous method of horizontal transport of muck was used, an intermittent horizontal transport method was also provided for underground haulage of men, materials, and supplies. In all cases, a manlift was provided in the shaft for personnel and a crane is used for lowering equipment, materials, and supplies through the shaft. Thus, all estimates include a complete material handling system suitable for all material handling requirements of the job.

TUNNEL JOB COSTS

The tunnel job costs obtained are summarized in Table 74. From this table, the following observations can be made:

1. A significant cost saving (about 35%) is indicated by increasing the average advance rate from 120 to 300 feet per day with a concurrent 4-fold increase in project size and tunnel reach.

2. The probability of major cost reduction in tunnel job cost resulting from substitution of alternative material handling system elements for the conventional railroad, crane or hoist of the base case appears to be small.

3. The variation in job cost resulting from introduction of various types of conveyors into the system is about 1.4 percent for the near term and 1.25 percent for the far term.

4. Substitution of pneumatic or hydraulic elements into the base case system appears to increase the job cost from 7 to 18 percent for the near term and 13 to 22 percent for the far term.

Improved perception of the job costs can be obtained by rearrangement of the computer output to provide Tables 75 through 78. In these tables, the job cost elements which are independent of the type of material handling system have been separated from those cost elements which vary with the muck transport system type. The nonvariable costs which are dependent only on the size of the job (assuming consistent methods of excavation and ground support) are the cost of all non-material-handling functions and the cost of tunnel muck disposal, which is assumed to be subcontracted at $3.00 per yard for surface haulage and disposal. If the computer output shows a variation

TABLE 74. TUNNEL JOB COST

Various Muck Transport Systems

Muck Transport Mode		Job Cost, $\$10^6$		Cost per Tunnel Foot, \$/ft	
Horizontal	Lifting	Near Term 20,000 TF	Far Term 80,000 TF	Near Term	Far Term
Rail	Crane/Hoist	10.08	25.17	504	315
Conveyor	Crane/Hoist	10.05	25.46	502	318
Conveyor	Pneumatic	10.83 (10.72)	28.55 (28.84)	541 (536)	357 (361)
Pneumatic	Pneumatic	11.51 (11.17)	31.27 (31.48)	576 (559)	387 (393)
Hydraulic	Hydraulic	11.92	30.68	596	383
Rail	Covered Belt	9.95	25.10	498	314
Rail	Steep Conveyor	10.01	25.40	500	317
Rail	Bucket Elevator	10.04	25.14	502	314
Rail	Inclined Conveyor	10.07	25.28	504	316
Rail	Spiral Conveyor	10.09	25.39	505	317
Rail	Pneumatic	(11.18)	(27.37)	(559)	(342)

Note:

1. Discrepancies between the job cost and cost per tunnel foot are due to rounding of numbers. The costs per tunnel foot reported are those calculated by the computer.
2. TF = Feet of tunnel length.
3. Numbers in parentheses are based on design and cost data provided by Radmark Engineering.

TABLE 75. TUNNEL JOB COST, NEAR TERM

Various Material Handling Systems

Cost Element / Horizontal → Vertical →	Tunnel Job Cost, Thousands of 1978 Dollars						
	Rail Crane	Conveyor Crane	Conveyor Pneumatic	(Conveyor Pneumatic)	Pneumatic Pneumatic	(Pneumatic Pneumatic)	Hydraulic Hydraulic
Non-Material-Handling	7,163	7,163	7,163	7,163	7,163	7,163	7,163
Tunnel Muck Disposal (SC @ $3/CY)	678	678	678	678	678	678	678
Total Nonvariable	7,841	7,841	7,841	7,841	7,841	7,841	7,841
Material Handling, Variable							
Direct Operating Labor	944	675	806	(723)	723	(640)	795
Operation and Maintenance	426	432	383	(312)	700	(801)	683
In and Out	248	276	206	(227)	258	(288)	354
Insurance and Taxes	127	142	187	(176)	276	(181)	309
Development Excavation	93	93	447	(447)	447	(447)	0
Job Impacts	0	8	61	(60)	61	(60)	73
Total MH other than Capital Items	1,838	1,610	2,090	(1,945)	2,465	(2,417)	2,214
Capital Items Amortized	398	596	898	(930)	1,205	(913)	1,865
Total Material Handling, Variable	2,236	2,206	2,988	(2,875)	3,670	(3,330)	4,079
Total Job (Amortized MH)	10,077	10,047	10,928	(10,716)	11,511	(11,171)	11,920
Plus MH Equipment Salvage	1,367	1,436	1,901	(1,756)	2,740	(1,451)	2,827
Total Job (0% MH Salvage)	11,444	11,483	12,730	(12,472)	14,251	(12,622	14,746
Minus MH Equipment Purchase	1,765	2,032	2,800	(2,686)	3,945	(2,364)	4,691
Total Job (100% MH Salvage)	9,679	9,451	9,930	(9,786)	10,306	(10,258)	10,055

Note: Numbers in parentheses are based on design and cost data provided by Radmark Engineering.

TABLE 76. TUNNEL JOB COST, NEAR TERM

Rail with Various Muck Lifting Systems

Cost Element / Horizontal → Lifting →	Tunnel Job Cost, Thousands of 1978 Dollars						
	Rail Crane	Rail Covered Belt	Rail Steep Conv.	Rail Bucket Elev.	Rail Inclined Conv.	Rail Spiral Conv.	(Rail Pneumatic)
Non-Material-Handling	7,163	7,163	7,163	7,163	7,163	7,163	7,163
Tunnel Muck Disposal (SC @ $3/CY)	678	678	678	678	678	678	678
Total Nonvariable	7,841	7,841	7,841	7,841	7,841	7,841	7,841
Material Handling, Variable							
Direct Operating Labor	944	798	800	799	802	799	(858)
Operation and Maintenance	426	364	360	417	362	384	(974)
In and Out	248	353	341	353	344	361	(424)
Insurance and Taxes	127	114	115	118	116	131	(249)
Development Excavation	93	97	165	107	223	105	(13)
Job Impacts	0	<17>	<17>	<17>	<17>	<17>	(<17>)
Total MH other than Capital Items	1,838	1,709	1,764	1,777	1,830	1,763	(2,501)
Capital Items, Amortized	398	405	403	418	403	490	(838)
Total Material Handling, Variable	2,236	2,114	2,167	2,195	2,233	2,253	(3,339)
Total Job (Amortized MH)	10,077	9,955	10,008	10,036	10,074	10,094	(11,180)
Plus MH Equipment Salvage	1,367	1,187	1,184	1,213	1,183	1,352	(2,106)
Total Job (0% MH Salvage)	11,444	11,142	11,192	11,249	11,257	11,446	(13,286)
Minus MH Equipment Purchase	1,765	1,592	1,587	1,631	1,586	1,841	(2,944)
Total Job (100% MH Salvage)	9,679	9,550	9,605	9,618	9,671	9,605	(10,342)

Note: Numbers in parentheses are based on design and cost data provided by Radmark Engineering.

TABLE 77. TUNNEL JOB COST, FAR TERM

Various Material Handling Systems

Cost Element / Horizontal → Vertical →	Tunnel Job Cost, Thousands of 1978 Dollars						
	Rail Hoist	Conveyor Hoist	Conveyor Pneumatic	(Conveyor Pneumatic)	Pneumatic Pneumatic	(Pneumatic Pneumatic)	Hydraulic Hydraulic
Non-Material-Handling	17,432	17,432	17,432	17,432	17,432	17,432	17,432
Tunnel Muck Disposal (SC @ $3/CY)	2,772	2,772	2,772	2,772	2,772	2,772	2,772
Total Nonvariable	20,204	20,204	20,204	20,204	20,204	20,204	20,204
Material Handling, Variable							
Direct Operating Labor	1,530	1,636	1,279	(1,279)	1,158	(1,033)	1,365
Operation and Maintenance	1,234	1,035	858	(696)	2,505	(4,265)	2,856
In and Out	649	645	431	(486)	408	(465)	631
Insurance and Taxes	298	320	440	(436)	712	(467)	779
Development Excavation	93	93	3,309	(3,309)	3,309	(3,309)	0
Job Impacts	0	101	22	(21)	22	(21)	20
Total MH other Than Capital Items	3,804	3,830	6,339	(6,225)	8,114	(9,560)	5,651
Capital Items, Amortized	1,159	1,428	2,006	(2,410)	2,950	(1,714)	4,825
Total Material Handling, Variable	4,963	5,258	8,345	(8,635)	11,064	(11,274)	10,476
Total Job (Amortized MH)	25,167	25,462	28,549	(28,839)	31,268	(31,478)	30,680
Plus MH Equipment Salvage	2,873	3,134	4,499	(4,174)	6,565	(2,531)	6,043
Total Job (0% MH Salvage)	28,040	28,596	33,048	(33,013)	37,833	(34,009)	36,723
Minus MH Equipment Purchase	4,032	4,562	6,505	(6,585)	9,515	(4,245)	10,868
Total Job (100% MH Salvage)	24,008	24,034	26,543	(26,428)	28,318	(29,764)	25,855

Note: Numbers in parentheses are based on design and cost data provided by Radmark Engineering.

TABLE 78. TUNNEL COST, FAR TERM

Rail with Various Muck Lifting Systems

Cost Element / Horizontal → Lifting →	Tunnel Job Cost, Thousands of 1978 Dollars						
	Rail Hoist	Rail Covered Belt	Rail Steep Conv.	Rail Bucket Elev.	Rail Inclined Conv.	Rail Spiral Conv.	(Rail Pneumatic)
Non-Material-Handling	17,432	17,432	17,432	17,432	17,432	17,432	17,432
Tunnel Muck Disposal (SC @ $3/CY)	2,772	2,772	2,772	2,772	2,772	2,772	2,772
Total Nonvariable	20,204	20,204	20,204	20,204	20,204	20,204	20,204
Material Handling, Variable							
Direct Operating Labor	1,530	1,537	1,558	1,554	1,534	1,554	(1,393)
Operation and Maintenance	1,234	1,309	1,298	1,323	1,246	1,329	(2,965)
In and Out	649	618	636	625	634	662	(636)
Insurance and Taxes	298	284	300	275	293	309	(474)
Development Excavation	93	102	237	121	324	117	(45)
Job Impacts	0	(49)	0	0	(84)	0	(<52>)
Total MH other than Capital Items	3,804	3,801	4,029	3,898	3,947	3,971	(5,461)
Capital Items, Amortized	1,159	1,093	1,166	1,031	1,131	(1,216)	(1,705)
Total Material Handling, Variable	4,963	4,894	5,195	4,937	5,078	5,187	(7,166)
Total Job (Amortized MH)	25,167	25,098	25,399	25,141	25,282	25,391	(27,370)
Plus MH Equipment Salvage	2,873	2,690	2,837	2,580	2,767	2,938	(3,862)
Total Job (0% MH Salvage)	28,040	27,728	28,236	27,721	28,049	28,329	(31,232)
Minus MH Equipment Purchase	4,032	3,783	4,003	3,619	3,898	4,154	(5,567)
Total Job (100% MH Salvage)	24,088	23,945	24,233	24,102	24,151	24,175	(25,665)

Note: Numbers in parentheses are based on design and cost data provided by Radmark Engineering.

in the non-material-handling cost element, it is adjusted to the value of the base case by adding a positive or negative cost to the variable material handling element identified as "job impacts." This is justified, since any variation in the excavation, ground support or overhead costs resulting from substitution of material handling system elements should be considered a cost of the material handling system.

The material handling costs which vary from system to system include direct operating labor, operation and maintenance, in and out costs, insurance and taxes, development excavation, job impacts, and the portion of the material handling equipment purchase cost which is charged to the job. Direct operating labor includes the cost of the work crews for operation of the material transport system during tunnel excavation (164 WD, NT; 254 WD, FT: Base Case);* the cost of the same crew during the 31-workday period (NT and FT) in which the mole and other equipment are moved from the first to the second tunnel bore; and incidental overtime costs. The crews include those required at the heading, at the shaft, and on the surface.

Operation and maintenance includes labor for material handling equipment repair, maintenance parts and supplies, and energy cost during materials transport, Saturday maintenance and movement of the mole. Some incidental overtime also is included. In and out costs include crane rental for raising and lowering materials through the shaft during installation and removal of equipment, freight for shipment of material handling equipment to and from the site, and labor for erection and removal of material handling equipment.

Insurance and taxes include the insurance premium for the duration of the job on the value of the material handling equipment and the sales and inventory taxes on this equipment.

The cost of excavation of the initial development area is allocated primarily to the non-material-handling cost element since it is required to initiate the tunnel excavation. However, some material handling systems may require a development area larger than the basic development area. If this is the case, the cost of the additional development excavation including the cost of boreholes or shafts used for pipe systems is charged to the material handling variable costs, since it is a result of the selection of that particular system. The development excavation cost includes the cost of direct labor for the drill-and-shoot crew including a load-haul-dump operator, the shaft crew including a crane operator and front end loader operator, equipment operation and maintenance costs, and the subcontract cost for muck disposal.

The sum of these variable material handling costs and the variable job impacts gives the total material handling cost other than costs for capital items (the amortized cost charged to the job for material handling equipment.)

*WD = work days, NT = near term, FT = far term

The selection of the portion of equipment cost to be charged to the job is a matter of judgment and will vary from job to job. This selection can have a large effect on the cost of the material handling system since the equipment purchase cost ranges from about .9 to 2 times the sum of the other material handling costs.

The capital items cost charged to the job is the sum of item-by-item costs derived by subtracting an estimated salvage value from the estimated equipment purchase cost. Thus, the total material handling variable cost is the sum of the material handling costs other than capital items and the amortized capital items cost. Since the capital items cost charged to the job is highly judgmental and will differ from contractor to contractor, it is beneficial to display the job costs under the two extreme assumptions of (a) no salvage value for the material handling equipment at job completion, that is, the entire cost of the material handling equipment is charged to a single job, and (b) the material handling equipment does not depreciate during the job, that is, the contractor can resell it for the same price that he paid for it and does not charge any of the purchase price to the job. These cost items are shown in Tables 75 through 78.

COST VS. SALVAGE VALUE

An improved visual comparison of the job costs can be obtained by plotting the data of Tables 75 through 78 as explained by Figure 33. In this graphic display, the total job cost in millions of dollars is plotted versus the total material handling system salvage value in percent. The nonvariable job costs are indicated by the dashed horizontal line labeled "non-material-handling plus tunnel muck disposal." The difference between the cost at this line and the right-hand ordinate of the total system cost is the material handling variable cost other than capital items, since for 100 percent salvage, no capital cost is charged to the job. The difference between the right-hand ordinate and the left-hand ordinate of the total job cost is the purchase cost (capital cost) of the material handling system. The difference between the right-hand ordinate and the value of total job cost read at any desired percent salvage is the amortized material handling system cost charged to the job. Thus, the total job cost for any assumed salvage value (or depreciation) of the material handling system can be obtained from the graph.

The cost data derived from the job estimates for the near term cases are plotted in Figures 34 and 35, and for the far term cases in Figures 36 and 37. The ordinate scale has been expanded in Figures 35 and 37 to provide improved resolution of the closely grouped job costs. The ticks at the right and left borders of Figures 35 and 37 represent the range of job costs (except for pneumatic lifting) in Figures 35 and 37, respectively.

It can be observed that the systems with hydraulic and pneumatic elements show higher job costs and generally higher purchase costs (steeper slope of job cost line), higher capital job charges, and higher noncapital costs (higher job cost at 100% salvage). In some cases, the capital cost charged to the job is increased by the lower salvage value associated with the system. But in no case would an increased salvage value (up to 90% salvage) make the system competitive with the systems not using the hydraulic or

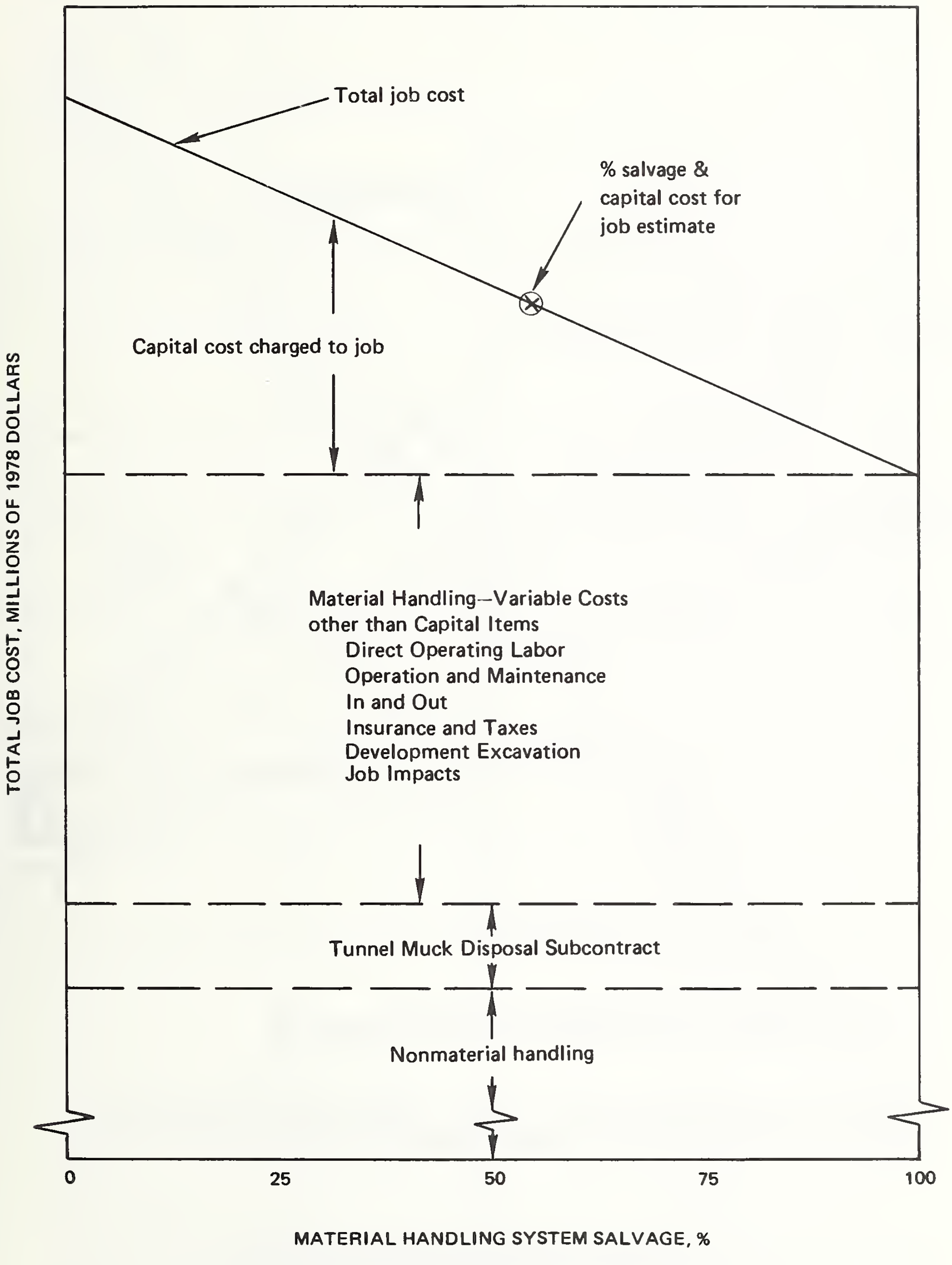


FIGURE 33. TUNNEL JOB COST, TYPICAL

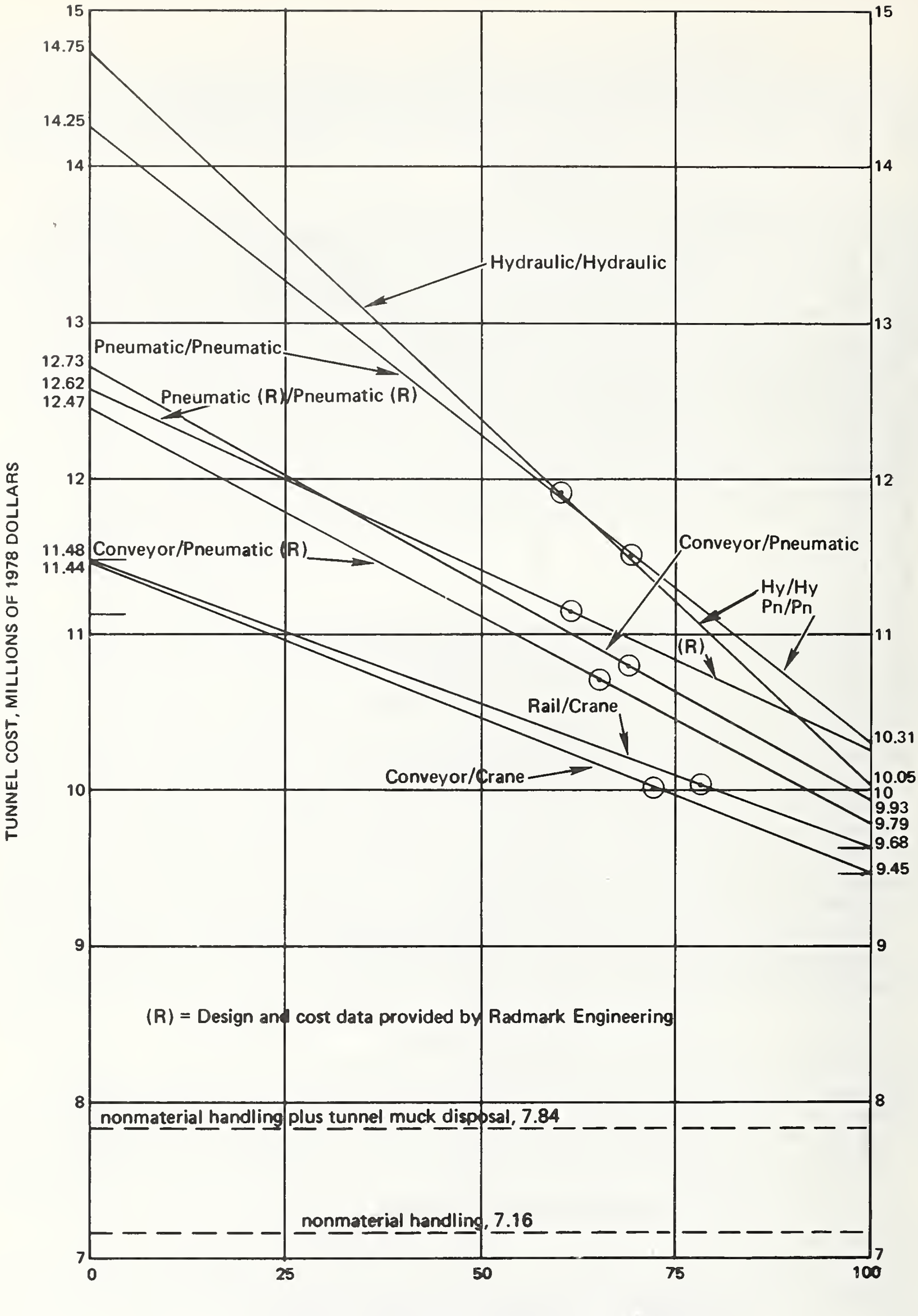


FIGURE 34. TUNNEL JOB COST, NEAR TERM
Various Material Handling Systems

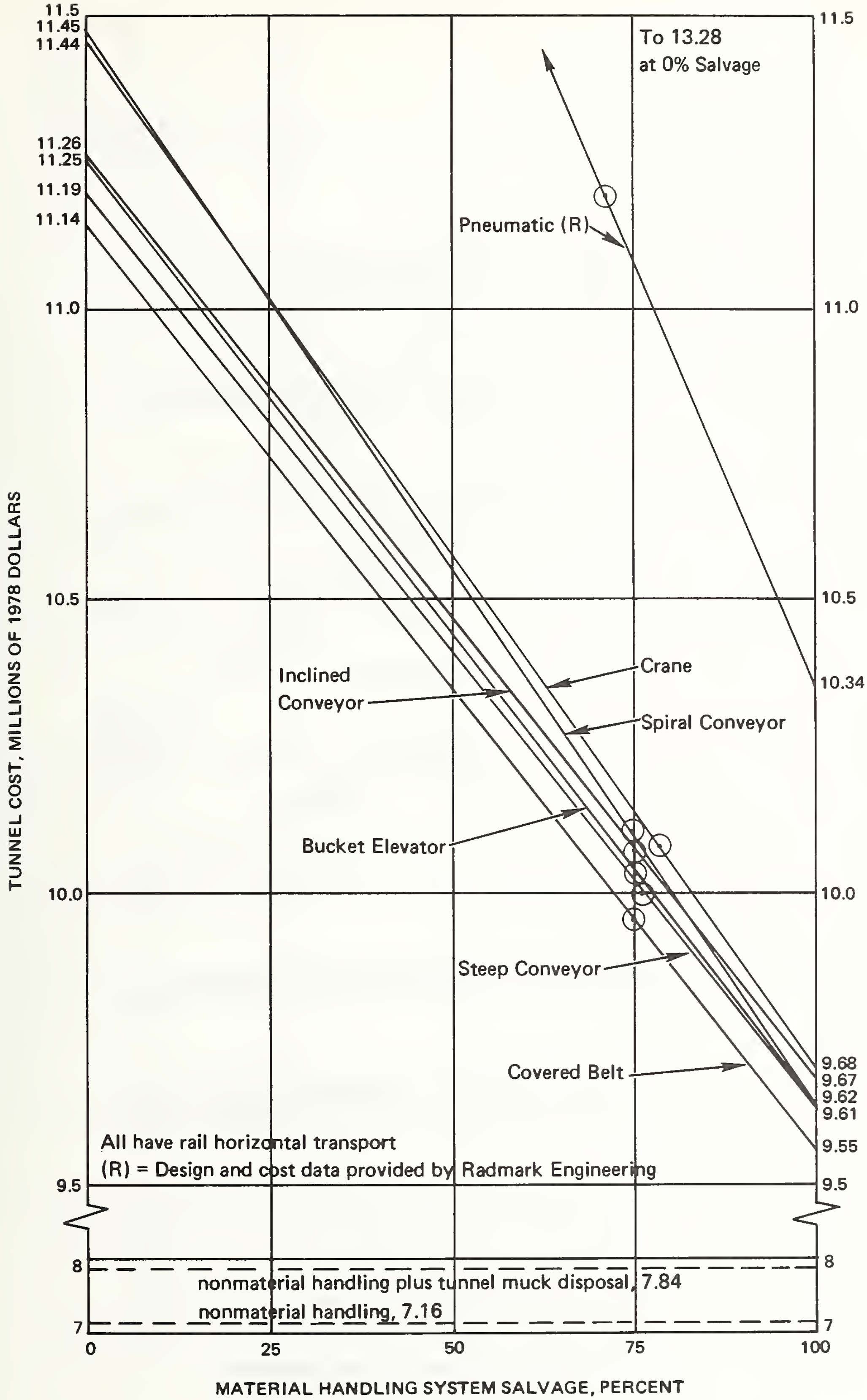


FIGURE 35. TUNNEL JOB COST, NEAR TERM
Various Muck Lifting Systems

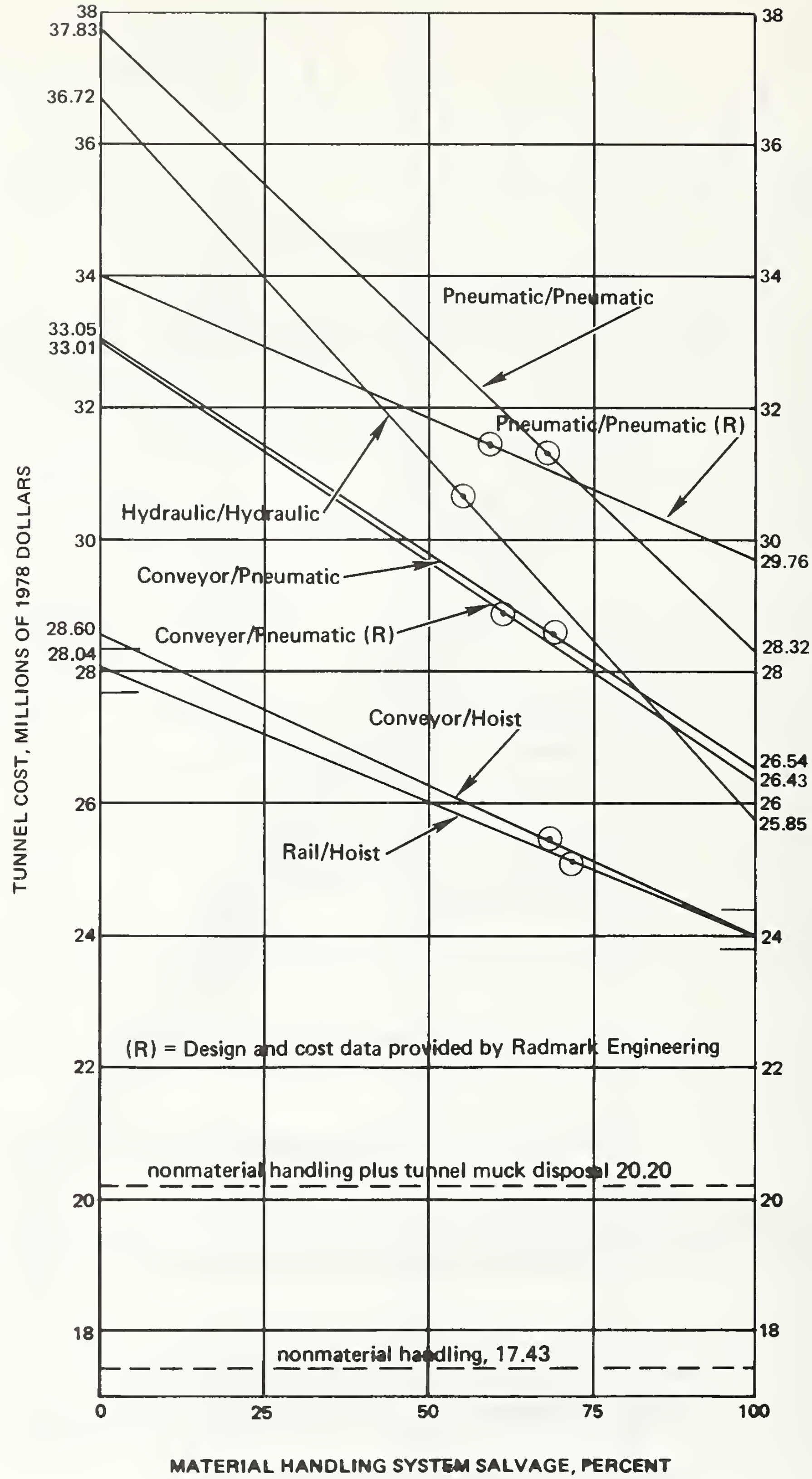


FIGURE 36. TUNNEL JOB COST, FAR TERM
Various Material Handling Systems

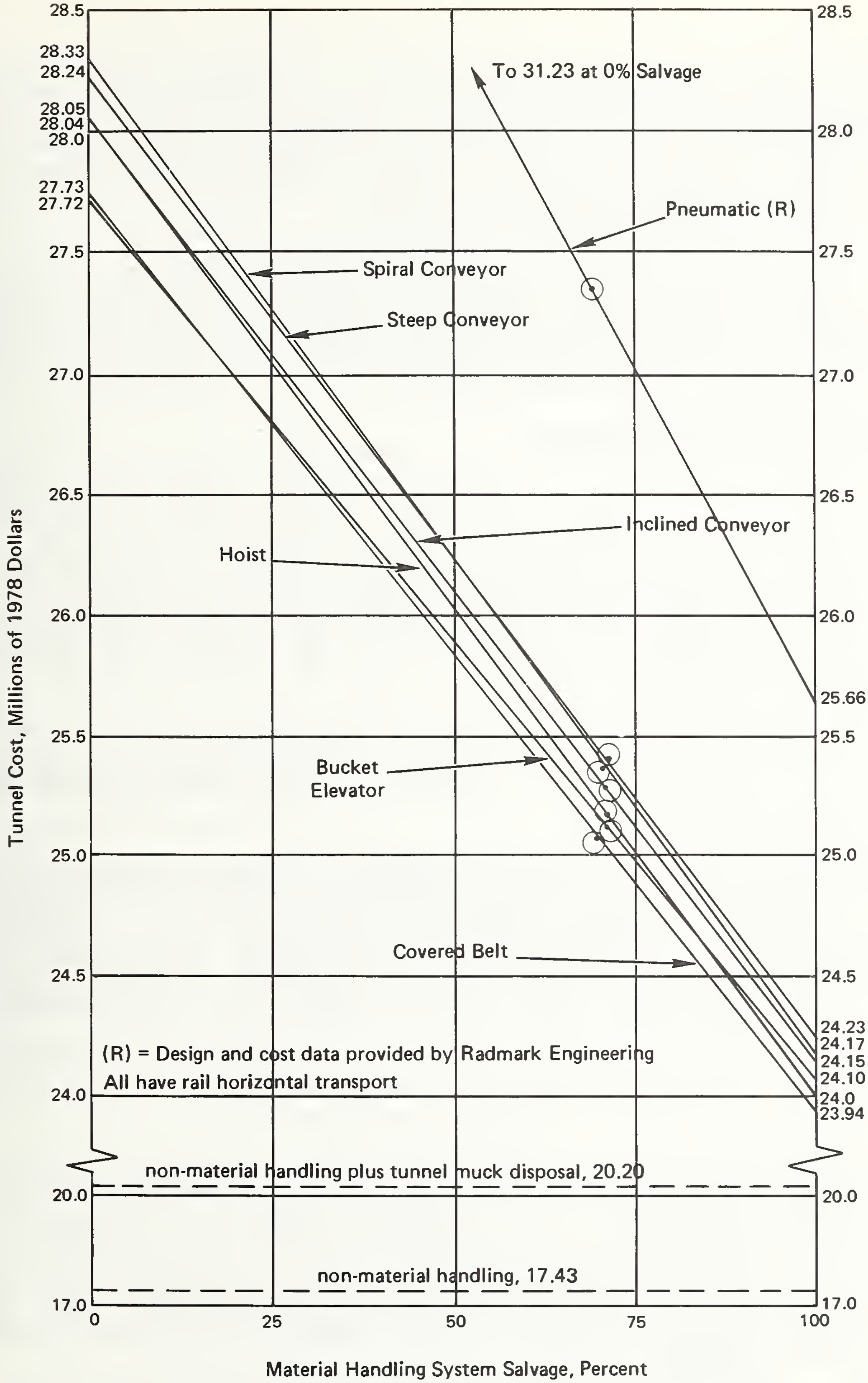


FIGURE 37. TUNNEL JOB COST, FAR TERM
Various Muck Lifting Systems

pneumatic elements. One factor contributing to the high capital cost of the pneumatic and hydraulic systems is the use of a rail system for horizontal transport of incoming materials. A rail system was judged to be necessary to transport and install the horizontal pipe sections and large equipment. When the conveyor system is used for horizontal muck transport, a special rubber-tired vehicle was judged to be adequate for incoming materials, since conveyor support elements are relatively small.

It is of interest to note that the pneumatic system appears to provide a lower job cost for the near term case than provided by the hydraulic system but the pneumatic system loses this advantage for the far term case. This is due primarily to the much larger amount of expendable pipe (a noncapital item) and the number of bore holes required for the far term pneumatic case.

VARIABLE MATERIAL HANDLING COSTS

To obtain improved visibility of the relative magnitudes and comparison of the material handling costs, the variable costs including the amortized capital costs have been plotted as bar charts in Figures 38 through 41. Expanded cost scales have been used in Figures 39 and 41 to obtain better resolution for the comparison of lifting systems. The narrow range of variable costs for the lifting systems (except pneumatic) is indicated by the ticks at the right borders on Figures 38 and 40 for the near term and far term cases, respectively.

The job impact cost, which increases the total job cost in some cases and reduces the total job cost in other cases (indicated by downward pointing arrows on the bar chart) is quite small and has only a minor effect on the relative cost of the systems.

The category of insurance and taxes consists of three components: an insurance premium paid on the average value during the job of the materials handling equipment, an inventory tax on the average value of the equipment, and a sales tax on the purchase cost of parts, supplies, and equipment. The sales tax is the largest component (about 75-80 percent) of insurance and taxes, so this item tends to vary with the purchase cost of the equipment.

In and out costs are roughly the same for all systems, but reflect the somewhat higher cost of installation of a hoist system (Figure 40) and the lower installation cost for a crane (Figures 38 and 40).

Development excavation costs vary from zero for the hydraulic systems (Figures 38 and 40) to about 40 percent of the total variable costs for the far term conveyor-pneumatic case. This increased cost for development excavation in the pneumatic cases (Figures 38 and 40) is due to the large number of cased bore holes used to transport muck to the surface. The larger development excavation costs shown for the inclined conveyor and steep conveyor systems (Figures 39 and 40) are due to excavation of inclined shafts for the conveyor systems.

A significant portion of the operation and maintenance cost of those systems using rail for horizontal muck transport (particularly the far term case) is the cost of operation of the ventilation system required for the

locomotives. When continuous systems are used for horizontal muck transport, the ventilation requirement is reduced to that required for operations at the heading. The ventilation required at the heading is also adequate for the locomotives or rubber-tired vehicles used for transporting incoming materials. Therefore, no cost for ventilation system operation is charged to the material handling system. However, when a pneumatic system is used for horizontal muck transport, the cost of operation of the stower and blower and the cost of replacement pipe and fittings more than offset the cost savings from elimination of the ventilation cost. If a hydraulic system is used, it is the cost of operation of the pumps that more than offsets the ventilation cost savings. The net result is a large increase in the operation and maintenance cost (particularly in the far term case) when pipeline systems are used for horizontal muck transport (Figures 38 and 40)

The cost of direct operating labor, which is one of the major cost elements (particularly for the near term cases), is increased when crane, hoist, or rail systems are used. This is due, in part, to work rules associated with these equipment types.

The amortized capital costs charged to the job are significantly larger for the pipeline systems than for the conveyor or rail systems. This is due in part to the smaller salvage values (55 to 70 percent, Figures 34 and 36) assigned to these systems compared to those (70 to 80 percent, Figures 35 and 37) of the conveyor, rail, hoist, and crane systems. The major factor, however, is the much larger equipment purchase cost; for the hydraulic system it is more than 2.5 times the base case (Tables 75 and 77).

COMPARISON OF CONVEYOR AND RAIL SYSTEMS

Even with optimistic guidelines for estimating the conveyor system costs, the use of conveyor systems for horizontal transport of muck does not offer an obvious cost advantage over the baseline rail system (Figures 34 and 36). On the other hand, the performance conditions and labor productivity assumed for the far term rail/hoist system may be considered to be optimistic. Therefore, it can be concluded only that the two systems may be competitive. The capital cost of the conveyor system is greater than that for the rail system in both the near term and far term cases. This reflects the fact that a rubber-tired vehicle system to transport incoming materials is provided with the conveyor system.

Both conveyor and rail systems are recognized as high capacity systems. Either can handle up to 10,000 tons per hour without difficulty in surface applications. Thus, 400 tph or 900 tph systems are only beginning to use the capabilities of the concepts. However, with the single travel path and confines of a tunnel, the traffic required on a rail system can become a problem (complexity and safety) as the travel distance and muck rate increase long before the surface capabilities of the system are reached. The operating stress under increased distance and muck rate appears to be less for a conveyor system, assuming that the problem of system extension can be solved and that the rubber tired vehicle system does not become overloaded. Thus, the conveyor system might become more competitive if excavation breakthroughs occur resulting in muck production rates of 1800 to 3000 tph.

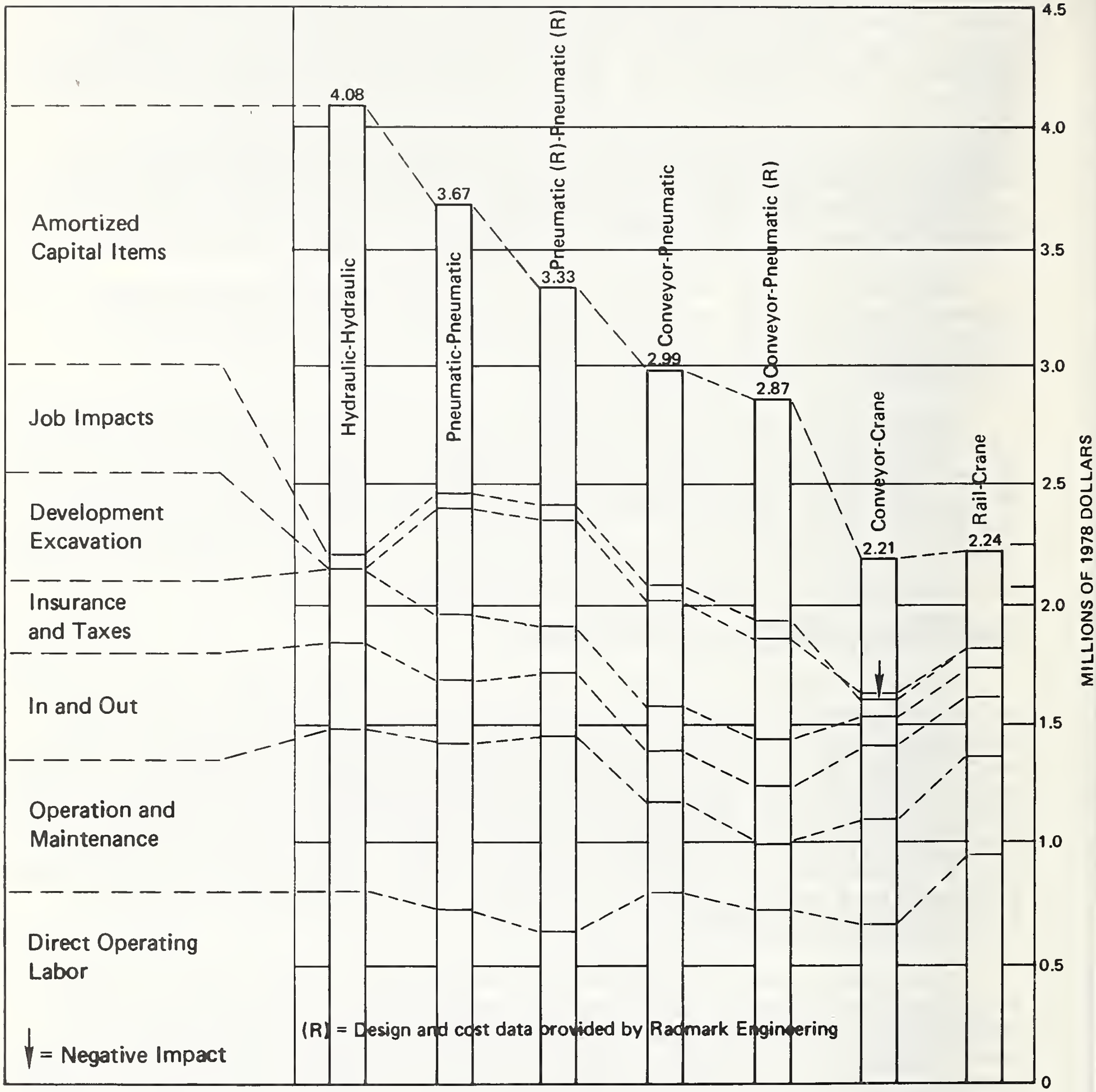


FIGURE 38. VARIABLE MATERIAL HANDLING COSTS
Near Term, Various Handling Systems

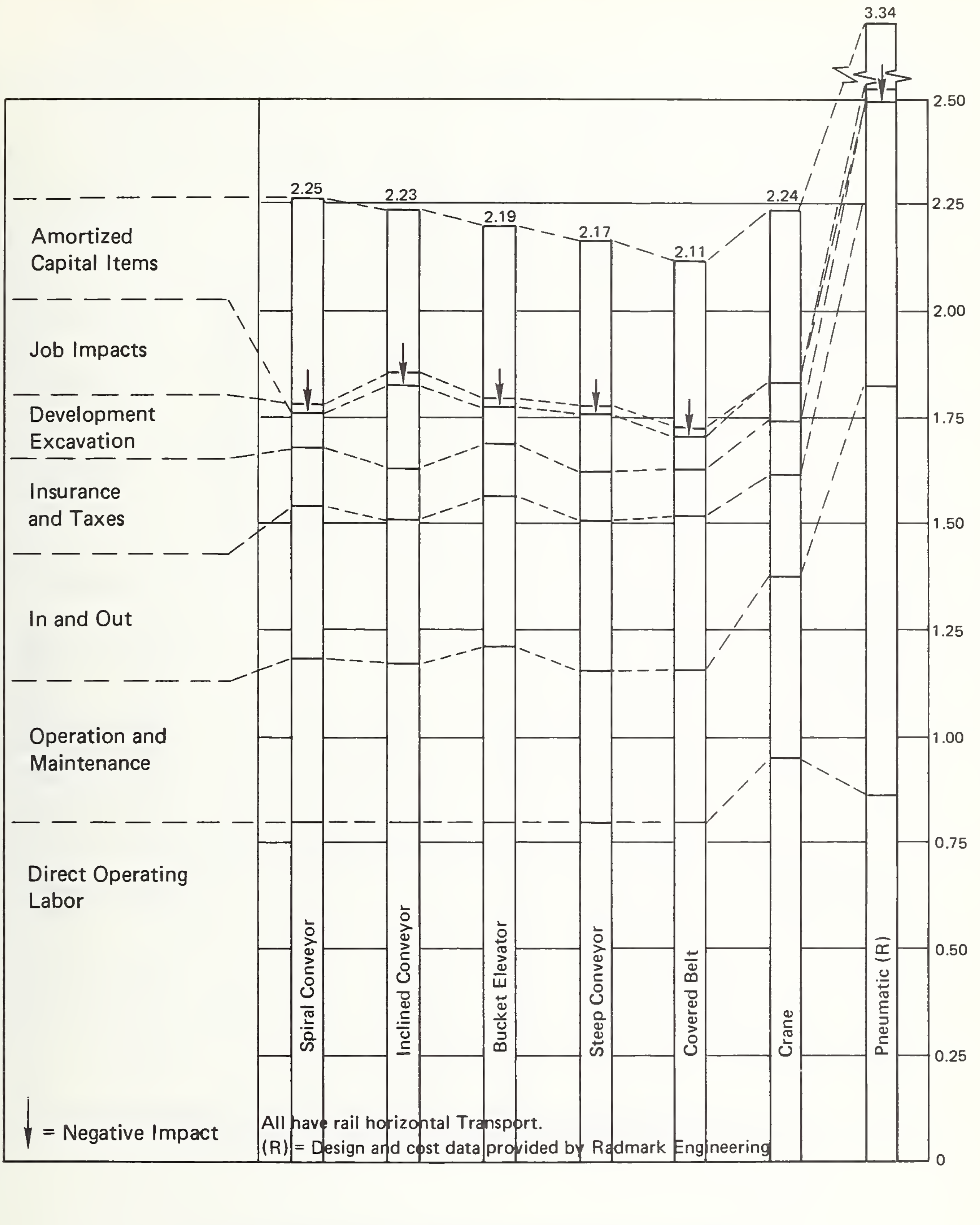


FIGURE 39. VARIABLE MATERIAL HANDLING COSTS
Near Term, Various Lifting Systems

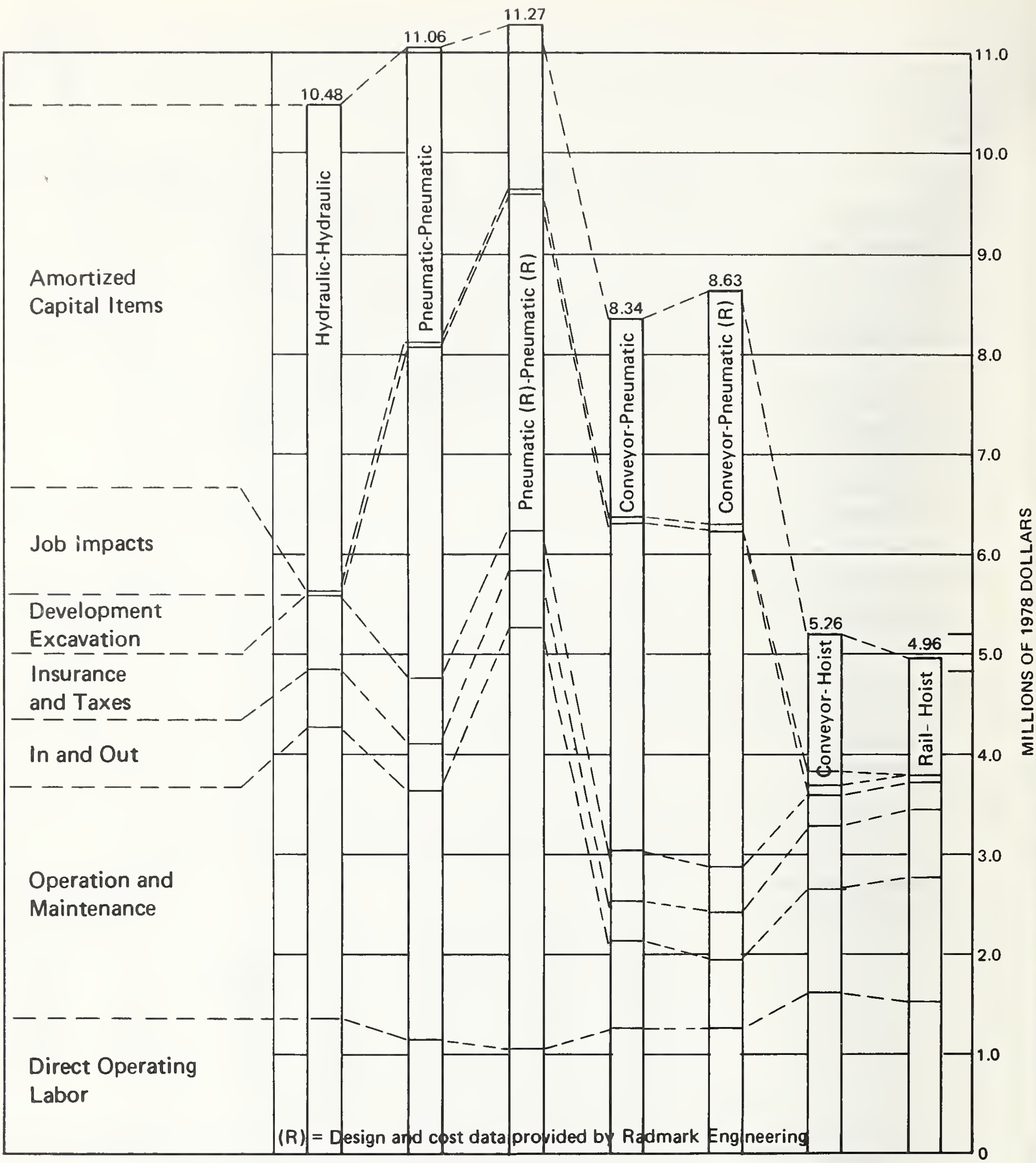


FIGURE 40. VARIABLE MATERIAL HANDLING COSTS
Far Term, Various Handling Costs

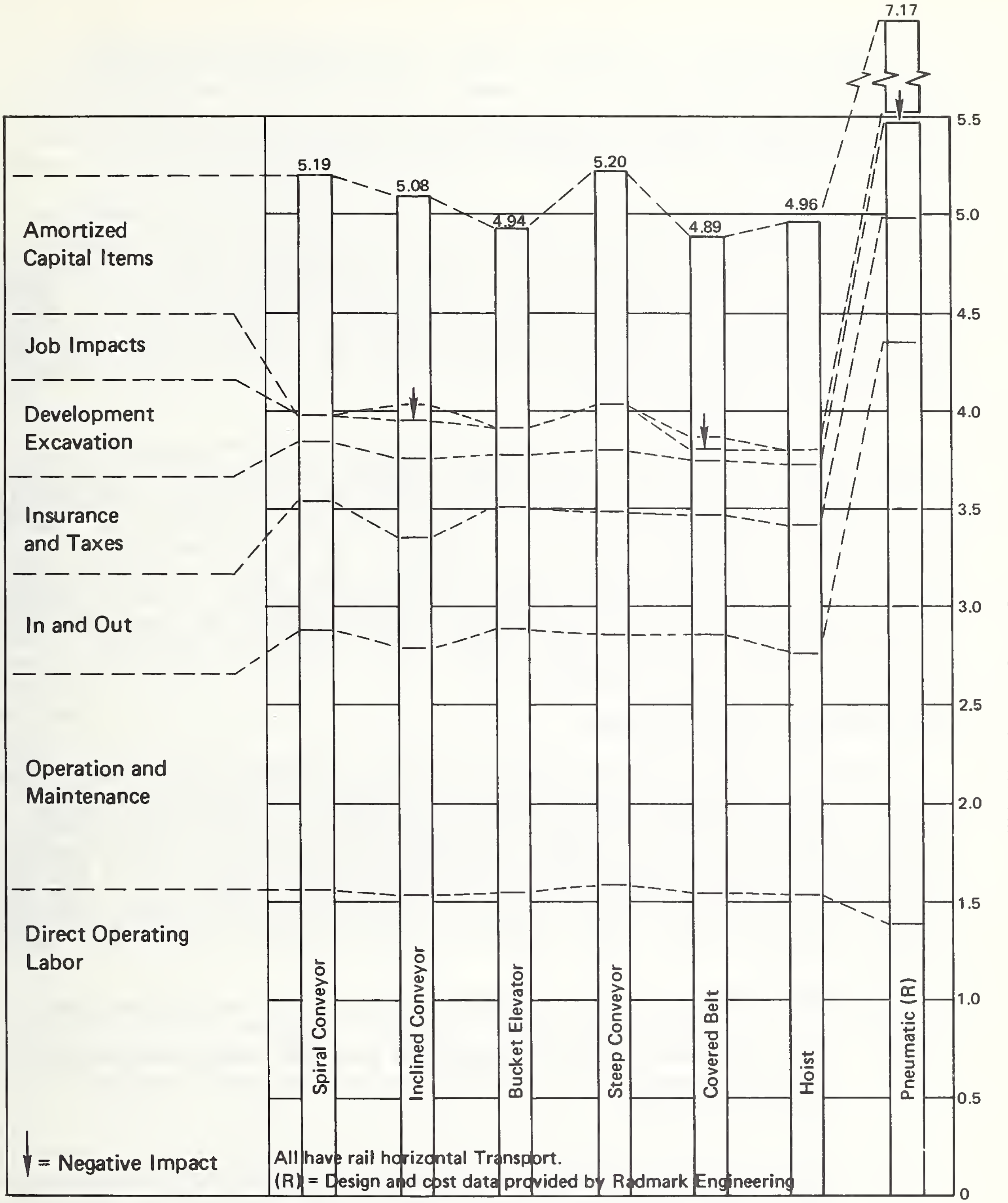


FIGURE 41. VARIABLE MATERIAL HANDLING COSTS
Far Term, Various Lifting Systems

Conveyor systems, in general, have a high investment cost which is proportional to the reach of the tunnel. This cost must be closely controlled if the conveyor is to be competitive with a rail system. As can be seen from Figure 34 and 36, multiple job use (high salvage value) of the conveyor system is essential for it to be competitive with the rail system.

It is difficult to predict crew requirements and operating costs for conveyors in the tunneling environment. For the system to be competitive these costs must not be greater than those for conveyors used in fixed mine installations. The estimate for the conveyor system demonstrates the disadvantage of using a single application (muck only) system for muck transport, which also requires a separately manned system for incoming materials. The cost of this system for incoming materials must be offset by cost savings from the muck transport system.

The cost of material handling per unit of muck removed is reduced significantly by increased job size and capacity of the material handling system. Comparison of the near term and far term rail systems shows the far term material handling cost to be 2.2 times that for the near term. However, four times the quantity of muck is transported in the far term case. Thus, the unit cost of material handling in the near term case is about 1.8 times that in the far term case even though the average distance of muck transport is 4 times greater in the far term case. This reduced cost (about 7-fold on a ton-mile basis) in the far term case is due primarily to improved utilization of men and equipment.

COMPARISON OF LIFTING SYSTEMS

Figures 39 and 41 show the results of cost estimates for various lifting systems. The costs shown represent all the variable costs for the total material handling system including the horizontal transport of muck and incoming materials. In all cases, horizontal transport is by rail, and the cost for horizontal transport for a given time period (near term or far term) is the same regardless of the type of lifting system used. Thus, differences in costs shown on either chart represent the differences in the costs of the lifting systems.

From Figures 39 and 41 and Tables 76 and 78, it can be observed that:

a. Indicated potential cost reductions from the base cases (crane/hoist) are small, less than $130,000 near term and less than $70,000 far term.

b. The maximum cost reductions are about 6 percent (near term) and 1.4 percent (far term) of the variable costs, and only 1.3 percent (near term) and 0.3 percent (far term) of the total job cost.

c. The maximum cost reductions represent a saving of about $6.50 per foot of tunnel for the near term and about $0.87 per foot of tunnel for the far term.

d. The use of a pneumatic lift system substantially increases the material handling cost.

e. In the near term case, all systems except the spiral conveyor and pneumatic system show potential savings over the crane system; in the far term case, only the bucket elevator and covered belt systems show potential savings.

In summary, it can be observed that although some alternative lifting systems appear to be competitive with the conventional crane or hoist systems, major cost reductions should not be anticipated. However, if a competitive alternative system were used for all or some of the muck lifting requirement, the stress on the capability of the intermittent lifting system would be relieved, particularly during periods of peak demand, thus giving greater assurance of reduced delays caused by the lifting system.

One of the major benefits obtained from the cost estimates is the insight provided to the cost factors which affect the job cost. For example, comparison of equipment costs can be obtained from Figures 35 and 37.

For the near term case (Figure 35), the purchase cost of equipment (slope of line) for all alternatives is essentially the same except for the pneumatic system, the spiral conveyor and the crane, which have higher purchase costs, with the spiral conveyor exceeding the crane and the pneumatic system exceeding the spiral conveyor. It is also observed that a higher salvage value has been derived for the crane than for any of the alternative systems, and that all the alternative system salvage values are essentially the same except for the pneumatic system which is lower. This higher salvage value for the crane system causes the amortized equipment cost charged to the job to be less than for any of the alternatives (Table 78), even though the equipment purchase cost is greater than that for most alternatives. If the salvage value for the alternative systems could be improved to equal that of the crane system, their competitive position (except pneumatic) would be improved. For example, the covered belt system job cost would be reduced by about $2.30 per tunnel foot; a total saving of $8.80 per tunnel foot compared to the crane system.

For the far term case (Figure 37, Table 78), the equipment purchase costs are more nearly the same, with the spiral conveyor being the only system more costly than the hoist. There is also insignificant difference in the salvage values derived.

In and out costs (about equally divided between shipping charges and installation and removal costs) are in the range of 55 to 75 percent of the amortized cost of the equipment. This provides an incentive to develop equipment which can be easily installed and removed at minimum cost.

The incremental cost of development excavation over that for the basic rail system is quite small except for those systems requiring separate inclined shafts (steep conveyor and inclined conveyor). The incremental development excavation for the inclined conveyor increases the job cost by $12 per tunnel foot in the near term case and $4 per tunnel foot for the far term case. This indicates that if the inclined shaft required for the

lifting system were part of the basic tunnel design (to be used as a ventilation shaft or station access shaft, for example) so its cost became part of the nonvariable job cost, the inclined conveyor system would become the least costly, in both the near term and far term cases.

The largest single cost element is the direct operating labor cost. This cost varies from 35 to 42 percent of the total variable cost for the near term case and 30 to 32 percent for the far term case. The following observations can be made:

a. The estimates include a significant material handling crew working on the surface. This cost element is the same for all cases.

b. When a continuous muck lifting system is used, a crane and related crew are required for incoming materials.

c. The largest crew size is required for the crane system. All other systems require about the same smaller crew size.

d. Energy costs for all lifting systems except pneumatic are about the same and are relatively insignificant.

e. Costs for parts and repair labor account for a large part of the operation and maintenance costs, which represent 15 to 25 percent of the variable costs. These costs are difficult to estimate for untried systems because of the lack of experience data for these systems in the tunneling environment.

f. High availability factors for all equipment that can delay the job are important, since the daily cost of direct labor only is about $8,700 for the near term case and $10,900 for the long term case. Indirect costs make the delay penalty significantly larger.

CONSIDERATIONS OTHER THAN COST

Equipment Versatility and Simplicity

Considerations other than job cost are usually important to the contractor in his selection of equipment. One of these considerations is the versatility of the equipment for application to other jobs (not necessarily tunneling) which the contractor may have or anticipate getting. The evaluation of the versatility of a particular equipment type will vary from contractor to contractor depending on the needs of each, but a listing from the most versatile to the least versatile might be as follows:

Crane
Rubber-tired vehicle
Rail-locomotive
Horizontal conveyor
Inclined conveyor
Hoist
Spiral conveyor

Covered belt conveyor
Steep conveyor
Bucket elevator
Hydraulic pipeline
Pneumatic pipeline

A contractor might be more reluctant to make a large investment in equipment at the bottom of the list than at the top.

Another form of versatility sought by the contractor is the ability of the material handling system to adjust to the material flow rate. Since the system is designed for the peak flow rate (or near the peak), it will be carrying less than its design capacity most of the time. A system which can accommodate this reduced flow rate with reduced operating cost is desirable. The intermittent systems (rail, rubber-tired, crane, hoist) have the greatest versatility in this regard. The hydraulic system is the least versatile, since a minimum critical velocity of water must be maintained to keep the solids in suspension. This results in a nearly constant operating cost regardless of the rate of material transported. Conveyors have some flexibility in this regard since the speed can be varied and the power requirement is to some degree load following. The power required by pneumatic pipelines is also load dependent.

The ability to add to existing equipment to extend the transport distance is also an important consideration. The extension of rail and rubber-tired vehicle systems is the simplest; the hydraulic system is the most difficult.

The ability to accommodate equipment failure with minimum interruption of material flow should also be considered. The rail system appears to be best in this regard; hydraulic, pneumatic or conveyor systems are the worst.

Simplicity of the total material transport system reduces the variety of operator skills required and the cost of spare parts and maintenance operations. The simplest total systems are those using the least number of transport modes with a minimum of supporting equipment and intermodal material transfers required. The simplicity of individual equipment components also contributes to overall system simplicity.

<u>Final Liner Installation</u>

Common present practice is to install a final concrete lining in urban transit tunnels after completion of the tunnel excavation. This is accomplished by starting the placement of concrete at the end of the tunnel reach and working back to the service shaft. This approach provides for delivery of concrete over the existing rail system and eliminates any need to work through the newly-lined segment of the tunnel.

If a rail system is not used during tunnel excavation, one would need to be installed for final liner installation or another means of concrete delivery would need to be used. Rubber-tired vehicles are generally considered unacceptable because of the large cross sectional area of conventional

transit mix trucks and the high cost of specially designed vehicles (at present not designed or developed). Even if such vehicles were developed, the traffic flow required would appear to create a hazardous situation, particularly in a tunnel with circular cross section.

Concrete has been transported for construction jobs by conveyor belt and it is conceivable that a conveyor belt system used for muck removal might be run in reverse to deliver concrete if the distance and time on the conveyor was short enough to avoid initial set of the concrete. Boreholes might be used at frequent intervals to pump concrete down to the tunnel where it could be delivered by conveyor or pumping. This would reduce the transit time. It appears unlikely that any part of the hydraulic or pneumatic system (other than boreholes) could be used for delivery of concrete for final liner placement. If precast concrete segments, installed at the time of excavation, are used as the final liner, the problem of post-excavation material handling is eliminated, but the transport of the liner segments is added during the excavation period.

Tunnels with Steep Grades

If gravity assisted acceleration/deceleration transit systems become a reality of the future, tunnel excavation and muck transport on 10 percent climbing and declining grades would become necessary. These sloping tunnel sections would be about 1000 feet long at the exits from and entrances to stations. Thus, for stations spaced 4000 feet apart, about 50 percent of the tunneling would be on a 10 percent grade. For a mole making a continuous bore of 10,000 feet or longer, the moling profile would be: decline 1000 feet, level 2000 feet, rise 1000 feet, level through the next station location, decline 1000 feet, and repeat the profile pattern to the end of the contracted reach.

With this profile for material transport it seems almost certain that the preferred strategy would be to remove muck to the surface at each station location rather than at a single access shaft, as is the present common practice. This implies that a system with minimum installation, removal and moving costs should be chosen for muck lifting. It also implies a horizontal muck transport system no longer than the maximum distance between stations and a system that can be moved ahead easily.

Rail systems are normally limited to grades of about 4 percent due to the limitation of the steel-on-steel tractive force. A traction assist system would be required to provide the necessary power on climbing grades and control the rate of descent on declining grades. In addition, a fail-safe breaking system would be required in the event of power failure while climbing or descending. Two approaches which have been used for many years for transport on steep grades are cable drive systems and cog (rack and pinion) drive systems. Cable drive systems can be either intermittent, powered by a drum or friction hoist, or continuous, powered by a bull wheel and continuous loop cable. In either case, for the loads involved, the travel rate would be relatively slow (5 mph or less) and the large size drive equipment required underground would add significantly to the congestion. Double tracking might be required on all grades due to the low travel rate.

The cogged rail system appears to have advantages over the cable system for this application even though it too is limited in speed to about 3 to 5 mph. If the system is double tracked on the grades, a continuous flow of muck trains could be maintained to avoid delaying the mole. More trains would need to be used than in the conventional case to compensate for the slower average rate of travel. The cog system would not require special operators at the grades as would be required by the cable system, and relocation of the cog system appears to be less costly than for the cable system.

A locomotive with cog drive and a positive action rail gripping brake system is estimated to cost about 40 percent more than a conventional locomotive, and the gear rack required for the track is estimated to cost about $20 per foot.

Grades of 10 percent cause no particular problems for conveyor, hydraulic, or pneumatic systems. However, additional power would be required to lift the muck from the greater depths reached by the profiled tunnel. The rubber-tired vehicles used for incoming materials with the conveyor system and perhaps with the hydraulic and pneumatic systems would have no difficulty with the 10 percent grades, but special provision might be required for fail-safe brakes.

Very rough cost estimates indicate that the material handling costs might be increased by about 10 percent if conveyor is used, about 15 percent if hydraulic or pneumatic is used, and perhaps 20 percent if rail is used.

ALTERNATIVE STRATEGIES

The typical strategy for mole excavation of twin tube tunnels with shaft access is to establish a construction support yard on the surface at the shaft and haul all muck from the heading to the support yard, where it is loaded into trucks for surface disposal. The twin bores are excavated in series with the mole penetrating the full length of the contracted reach in the first bore before being backed out to the shaft for excavation of the second bore. Thus, enouqh material transport equipment must be purchased to extend the full length of the contracted reach and, on the average, this equipment is used only about half the time. The muck lifting equipment is installed at the shaft and left in place throughout the excavation period.

Typically, tunnels of 10,000 feet or more in length pass through or by the location of one or more stations or ventilation shafts. Also, tunnels connecting the twin tubes are provided at intervals to reduce the "piston effect" during use of the subway. These characteristics of the subway tunnel design offer the opportunity for alternative material handling strategies during excavation.

Short Haul Muck Transport

One possible alternative to underground muck transport the full length of the tunnel reach, would be to move the muck lifting system forward to

shaft or station locations as excavation proceeds. This would allow the purchase of less equipment for muck transport and reduce the material transport system operating cost, since the average ton of muck would be transported a shorter distance underground.

Preliminary cost estimates indicate the possibility of a net reduction in material handling costs if this approach is used under certain conditions. These conditions include the assumptions that:

a. The project design calls for ventilation shafts or stations spaced fairly uniformly throughout the contract reach so that the cost of providing access at these intermediate points would not be charged to material handling.

b. Excavation for access at intermediate points is performed prior to mole excavation so that the access openings would be available when needed.

c. The principal construction yard will remain at its original location to avoid the cost of relocation.

d. Surface disruptions caused by equipment installation and truck loading at several points along the tunnel route will be acceptable.

e. The muck lifting system is designed to be portable to keep the relocation cost small.

The cost elements which would be reduced by this approach are:

a. Amortized capital charged to the job.

b. Insurance and taxes associated with the material handling equipment.

c. Operation and maintenance costs.

d. Direct operating labor.

For this approach to be viable, the cost reductions must exceed the cost increases due to:

a. Dismantling, moving, and reinstalling the muck lifting systems, including the aboveground equipment.

b. Dismantling, moving, and reinstalling any support equipment, such as dumpers and loaders associated with the horizontal transport equipment.

c. Delays caused by the relocation of equipment.

Rough cost comparisons indicate that net cost reductions might reach $20 per tunnel foot for design capacities of 400 tph and about $8 per tunnel foot for capacities of 900 tph, if two sets of equipment or highly portable lifting equipment are used to avoid job delays.

Cross Feeding Between Tunnels

Another approach which has been mentioned is to leave the muck transport system in place after the first bore is completed and, during evacuation of the second bore, transport muck from the heading back to the closest cross bore for transfer to the main haul system in the first bore. This would avoid relocation of the main haul equipment for excavation of the second bore. Cursory examination indicates little incentive for this approach since there is no apparent reduction in amortized equipment cost or operation and maintenance cost. In fact, equipment cost would appear to be slightly higher due to the added length of conveyor used in the second bore to reach the cross bore, the equipment required in the cross bore, and the equipment at the two transfer points at the ends of the cross bore. In addition to the addition of two transfer points, which is undesirable, this approach would interfere with material transport during installation of the final liner, and prevent removal of the rail system as the final liner was put in place.

If it were necessary to charge the cost of the cross bores to material handling, the concept is almost certain to show no net cost reduction.

EFFECT OF TUNNEL LENGTH ON COST

The major differences between the near term and far term cases which affect material handling cost are tunnel length, depth of tunnel, and advance rate (which determines the material flow rate). These three parameters changed simultaneously from the near term to far term cases, thus obscuring the effect on cost of any one of them.

To obtain an indication of the effect of tunnel length on the cost of horizontal transport of material, a parametric comparison was made using the near term (400 tph, 10,000-foot reach, 100 feet deep) and far term (900 tph, 40,000-foot reach, 200 feet deep) cases as a basis for cost estimates. Analysis of the basic estimates indicates that the cost elements fall in three categories:

1. Fixed costs that are essentially independent of tunnel reach and job duration (development costs, heading and shaft equipment, in and out costs, etc.).

2. Length variables that are almost directly proportional to tunnel reach (equipment extended along the tunnel reach, related costs, etc.).

3. Complex variables that change with tunnel reach and job duration, which is determined by advance rate (operating and maintenance crews, energy cost, etc.).

The basic cost estimates were adjusted by removing the material lifting costs to eliminate the tunnel depth variable. A parametric curve was developed for a capacity of 400 tph by adjusting the estimate for a 20,000-foot tunnel (2 reaches of 10,000 feet each) upward in increments of 20,000 feet of tunnel to a maximum of 80,000 tunnel feet (2 reaches of 40,000 feet each). These adjustments were made by a careful review of the length-variable and complex-variable costs of the base case (10,000-foot reach) and applying appropriate cost increases to each cost element. A similar procedure was applied to derive a parametric curve for a capacity of 900 tph by applying appropriate cost reductions to the cost elements of the base case (40,000-foot reach). This procedure was applied to derive curves for both rail haulage and conveyor haulage with rubber-tired vehicles for incoming materials. The results are shown in Figure 42.

While making interpretations of these curves, it should be kept in mind that:

a. System designs are not necessarily optimal and different degrees of optimism may be present in the designs for different capacities and modes of transport.

b. Differences are present in the degree of technological development assumed for the lower capacity and higher capacity cases.

c. To avoid the need for more detailed estimates, linear approximations were used in extending cost estimates from the base cases.

d. Variations in minor cost factors, such as taxes, insurance, mole movement, and job impacts, were not included in the cost adjustments.

The following observations can be made from Figure 42:

a. For short reaches (less than 20,000 feet) and low capacities (400 tph), the cost of horizontal transport by rail or conveyor appears to be about equal (within the limit of error of the estimates)

b. For longer reaches (above 25,000 feet) and low capacity, the cost of transport by conveyor becomes significantly greater (about 28 percent at 40,000 feet) than by rail.

c. For reaches less than 30,000 feet and high capacities (900 tph), conveyor transport appears to be less costly than train (about 13 percent at 20,000 feet, and 21 percent at 10,000 feet).

d. For very long reaches (above 34,000 feet) and high capacity, rail transport becomes less costly than conveyor.

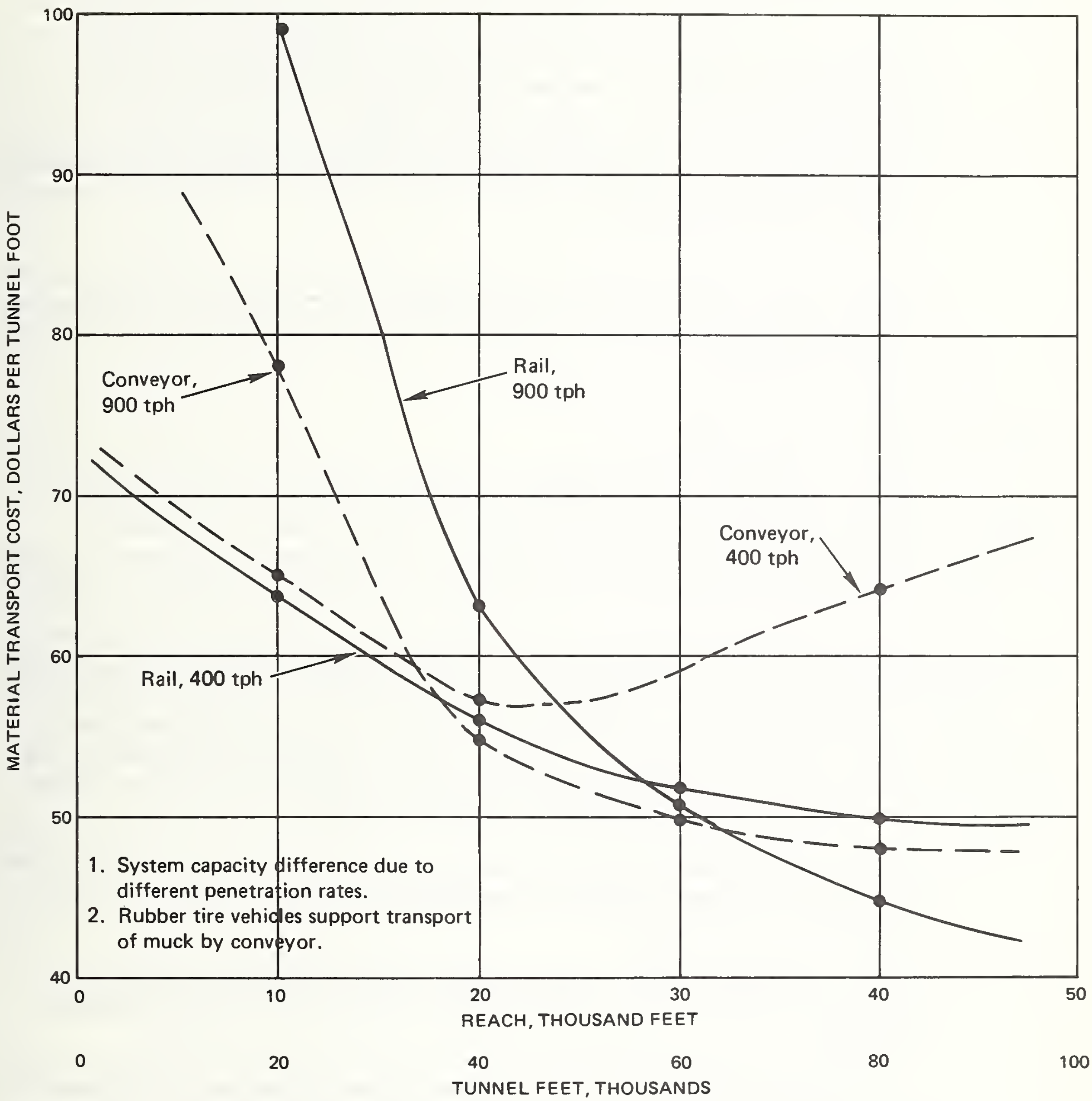


FIGURE 42. MATERIAL TRANSPORT COSTS VS TUNNEL LENGTH

e. In general, rail is less costly than conveyor for long reaches, with the preference for rail increasing as the reach becomes longer and the capacity becomes less. Conversely, the preference for conveyor becomes greater for shorter reaches and high capacities.

f. If the length of reach defined by job specifications does not increase as rapidly as the increase in penetration rate, the use of conveyor transport will become more favorable in the future.

g. The cost of muck transport per tunnel foot decreases significantly as the length of reach increases, except when low capacity conveyors are used in long reaches.

h. High capacity material handling costs more than low capacity if the reaches are less than about 20,000 feet. This may be an indication that increasing the penetration rate without defining longer reaches is not desirable.

TUNNEL DIAMETER AND MUCK RATE

If the tunnel diameter is changed but the penetration rate is unchanged the muck rate will change proportionally to the square of the diameter. Thus a 56 percent increase in muck rate will result from a 25 percent increase in diameter (20 feet to 25 feet) and a 44 percent decrease in muck rate will result from a 25 percent decrease of diameter (20 feet to 15 feet).

The material transport cost would be expected to increase with increased muck rate and decrease with reduced muck rate if penetration rate and length of reach are held constant. However, an examination of the cost estimating data for the base cases (rail and conveyor) indicates that the material transport cost is less sensitive, in short reach tunnels, to variations in muck rate due to diameter change than those due to penetration rate change. This is due, in part, to the following considerations:

a. Due to the low utilization of men and equipment, there is only small variation in crews or hourly operating cost with changes in the capacity of the system.

b. The net equipment cost changes very little with small capacity changes as long as the advance rate and length of reach remains constant.

c. Increased muck rate due to increased tunnel diameter is accompanied by an increase in working space and reduced congestion. Increased muck rate due to increased penetration rate is accompanied by a need for more rapid extension of the transport system and decreased job duration.

Although the muck rate decreases more rapidly than the diameter as smaller tunnels are excavated, it can be anticipated that a diameter is reached (perhaps around 15 feet) where the problems of congestion and the cost of reduced size equipment cause the cost of muck transport per tunnel

foot to rise, even though the quantity of muck is less. The effect would seem to be more pronounced in longer reaches. Increased muck rate due to increased penetration rate in small tunnels, particularly for long reaches where train passing is required, would result in high cost of material handling per tunnel foot. Under these circumstances, conveyors might compete more favorably with trains than in the larger tunnels.

In making comparisons between the effects on cost of different muck rates, the cause of the changed muck rate must be kept in mind, since other changes of job condition which also affect cost are associated with changes in tunnel diameter and changes in penetration rate.

16. RESEARCH AND DEVELOPMENT PROGRAM

The magnitude of a development program directed toward a specific goal should be commensurate with the benefit expected from achievement of that goal. The research and development program for improvement of material handling in urban tunneling has two goals: (1) to reduce the cost of tunneling by substitution of a more cost effective material handling system and (2) to assure that the material handling system will not become the limiting factor on the rate of excavation. The benefit expected from achieving these goals can be measured in dollars by estimating the reduced cost per linear foot of tunnel and applying this cost saving to the number of feet of tunnel anticipated for a specified time period.

Table 5 indicates that in the 25-year period from 1976 to 2000, tunneling in rock may be anticipated as 687,000 linear feet of tunnel for rapid transit systems and 1,755,000 linear feet for other applications such as water and sewer. Thus, less than 2.5-million tunnel feet of rock tunneling are anticipated for an average of less than 100,000 feet per year. These numbers could be high considering the rising cost of tunneling and the present thinking regarding mass transit systems.

Table 74 indicates a cost reduction in the near term case of 2 dollars per tunnel foot by substituting a conveyor/crane system for the conventional rail/crane system and a reduction of 6 dollars per tunnel foot by using a rail/covered belt system. If it is assumed that these cost savings are additive for a system using a conveyor/covered belt system, the maximum anticipated saving by substitution of material handling systems is 8 dollars a tunnel foot. This would produce a total saving of about 20 million dollars in a 25-year period. Since less than 25 percent of this saving would accrue to rapid transit tunnels, it is apparent that only the most modest development expenditure could be justified on this basis alone.

However, if it is assumed that the excavation rates (and hence job size) projected for the far term case would not be achieved without improvements in the material handling system, then the potential benefits become much greater. Table 74 indicates a cost reduction of about 190 dollars per tunnel foot for the far term case compared to the near term case. If it is assumed that less than one-half of this saving would be realized without a systematic development program to improve the material handling system, then the potential benefit from the development program becomes about 10 million dollars per year. About 2.5 million dollars per year would accrue to the urban mass transit tunnels. This potential benefit might justify an annual expenditure of something less than 1.5 million dollars per year in the interest of mass transit tunnels. If additional funding were obtained from other sources which would benefit from the reduced cost of tunneling, a more intensive program might be justified.

PROBLEMS AND R&D NEEDS

During discussions with manufaturers and contractors (33) and as a result of workshop panel deliberations (26) many specific problems and areas needing improvement were identified for the various material transport systems.

These suggested research and development needs are listed and briefly discussed in the following subsections.

1. General Items for R&D

a. Market Identification. (Determination of the market for material transport equipment designed for tunneling needs.)

The need for a good understanding of the potential market for a product before industry can risk substantial R&D funds in its development was mentioned frequently. A market survey should be conducted to identify the market potential for the various transport modes if developed to meet the needs of urban tunneling. Specific situations in which a particular transport mode might find application should be identified. For example, slurry transport would be particularly suited to situations where hydraulic excavation or bentonite moling was the preferred excavation method. The investigation should extend beyond urban tunneling to include tunneling for other applications and potential applications of the equipment in other fields such as mining, general construction and manufacturing industry. For industry to contribute significantly to the R&D effort, a continuous and long term market must be identified.

b. Ground Support Installation. (Study of the handling and installation of initial ground support.)

Several contractors identified the installation of initial ground support materials as a major cause of job delay. Handling and installation of these materials at the heading is an entirely different problem than the transport of materials to and from the heading. Very little systematic attention has been given to this problem. An in-depth study might identify improved methods for handling and installing these materials.

c. Crusher. (Development of a low profile, small size, large capacity breaker-feeder.)

The control and reduction of lump size is an important consideration for all continuous material transport systems. Most rock crushers of adequate capacity are large in size. Lower profile and smaller size are needed for equipment to be used in the heading.

d. Intermodal Transfer. (Study of intermodal transfer and surge storage problems.)

The benefit from development of improved transport modes will be reduced if problems exist at points of intermodal transfer. These problems for various combinations of transport mode (horizontal and vertical) should be identified and solutions sought.

e. Transport Equipment Designs. (Review of material transport equipment designs with the objective of making them simpler, more rugged and less costly.)

Many contractors feel that systems tend to become too complex and delicate for the tunnel environment. A review of designs might reveal low cost methods of improving ruggedness and system reliability and availability.

f. Handbook. (Development of a handbook of good practice for materials handling in tunneling.)

There is some feeling that many of the material transport problems could be eliminated by better job planning and improved selection and installation of transport equipment. A handbook of good practice was suggested as a possible means of improving job planning and execution. Development of such a handbook should lean heavily on the experience of tunneling contractors.

g. Tunnel Alignment. (Investigation of the potential for cost reduction and problems associated with short radius curves in tunnel alignment.)

Most urban tunnels tend to follow the alignment of surface streets to take advantage of public right-of-way. In many cases this causes the tunnel to have short radius curves which slows down the tunneling process. This problem should be investigated with the objective of developing urban tunnel alignments without short radius curves.

2. Conventional Rail Haulage

The Keystone Workshop panel for rail haulage concluded that there are no problems which would limit rail haulage up to 800 tph on grades of 5 percent or less provided diesel locomotives are used.

a. Derailment. (Study of derailment causes and solutions.)

Derailment was identified as one of the major problems for conventional underground rail haulage. A detailed study of causes and solutions including the roadbed, rolling stock, climber points, switches, rail spreading and speed, would contribute to a reduction in downtime caused by the rail haulage system. This study would also determine the true downtime caused by derailment and the potential savings resulting from its elimination.

b. Ventilation. (Study of ventilation requirements related to use of diesel power and alternative power sources.)

Schedule 24 sets arbitrary ventilation requirements for various equipments. There is some feeling among contractors that a ventilation requirement based on a performance specification would be more beneficial. The Keystone Workshop panel concluded that prohibition of diesel power would greatly increase the cost of tunneling, and the frequency and severity of accidents. The speed and flexibility of diesel power are considered to be very important. The question of diesel power and adequate ventilation should be investigated in cooperation with groups presently considering the question.

c. Live Axles. (Investigation of the use of live axles rather than dead axles on rail cars used in tunneling.)

Based on practices and experience of commercial railroads, there is some feeling that use of live axles rather than dead axles, as is now the practice in tunneling and mining, might reduce wear and derailments, and permit increased speed. This question should be investigated in theory and by demonstration, taking full advantage of prior work of the ASME comittee investigating wheel-rail interface problems.

d. Locomotives. (Investigation of improvements in underground locomotives.)

There is some feeling that the design of underground locomotives, which has changed very little over many years, could be improved. For example, the wheel base may be too short, an 8-wheel configuration might be better, and a locomotive with smaller cross section might be developed without decreasing power. The potential for improvements in underground locomotives should be investigated.

e. Muck Cars. (Investigation of problems of dumping muck cars and feeding to elevating transport mode.)

One of the biggest problems with muck cars is clean dumping when sticky materials are hauled. This problem remains unsolved although contractors have been harassed by it for many years. An investigation of the problems of dumping muck cars and muck boxes of various types and feeding to various elevating transport modes could yield potential solutions to this old problem. This study might be a part of the broader investigation of intermodal transfer problems.

f. Skip Cartridge. (Improvements in the skip cartridge for dumping muck boxes.)

The most common method of elevating muck from shallow tunnels is the crane lifted muck box. Skip cartridges have been developed to speed up the process of engaging and disengaging the muck box. There appears to be room for improvement in the design of most of these devices. A study to develop an optimized design for a skip cartridge could significantly reduce the cycle time for this mode of elevating and provide an elevating method adequate for many excavation situations.

g. Muck Size and Shape. (Development of improved methods or equipment for handling a wide variety of muck sizes and shapes while loading rail cars.)

Rail transport can handle a wide range of muck sizes and shapes without difficulty. However, the loading equipment is often adversely affected by these variables. Improved method or equipment for loading muck cars would contribute to better reliability for the horizontal transport mode. (This problem is common to all horizontal transport modes.)

h. Reliability. (Study of rail system reliability including causes of failure and corrective action methods.)

A reliability study of the rail haulage system would identify the weak links in the system so they could be corrected before becoming acute as the requirements for the system become more severe.

i. Track Laying. (Development of improved methods for track laying behind mole and during replacement.)

As the rate of advance of the mole increases it will become more difficult to lay track in pace with the advance. A study of improved methods (such as prefabrication of track sections) of track installation could solve this problem before it becomes critical.

j. Wear. (Determination of causes of and corrective action for excessive wear of climbing points, wheels, track and bearings.)

Excessive wear of wheel, track, bearings, climbing points and switches contributes to the operating and maintenance cost of a rail haulage system. A study of causes and corrective action could reduce these costs.

k. Safety. (Investigation of the impact on safety of increased train speed and frequency.)

Safety is a prime consideration in tunneling. As the advance rate increases requiring more trains traveling at higher speed, hazards will increase unless proper precautionary measures are taken. A study of the impact on safety of increased train speed and frequency should be initiated before the problem occurs.

l. Super Grades. (Investigation of problems and their solutions associated with grades greater than 4 percent, including power assist methods and control of runaways.)

If the gravity assist urban transit systems are adopted, tunneling will be required through profiles with grades up to 10 percent. The material handling problems associated with these grades would need to be investigated in detail before undertaking tunneling under these conditions.

3. Hoisting

The Keystone Workshop panel for hoisting felt that the equipment and application technology presently available is adequate for present day mining and construction shaft hoisting but that there appears to be a problem of distribution of this knowledge especially in the area of shallow shaft hoisting. The Holmes & Narver, Inc. survey indicates a feeling among tunnel contractors that hoisting through the shaft is or will become the limiting factor for material handling in tunnels greater than 15 feet in diameter.

a. Survey of Hoisting. (Survey of the state of the art for hoisting in shallow shafts including problems of design, equipment selection and application.)

A survey of hoisting (in greater detail than the present study) should include a review of existing methods and equipment (cranes, conventional

hoists, hydraulic hoists) in shallow shafts (less than 500 feet); design requirement for tunneling application; safety considerations; economics of hoisting (manning, capital and operating costs, productivity); current, pending and needed legislation; and future needs.

b. Loading and Dumping. (Study of loading and dumping for hoisting.)

Loading and dumping, particularly if the material is sticky, can become a severe problem and extend the cycle time. When muck boxes are lifted, engaging and disengaging the box is a major element of the cycle time. These problems should be investigated in detail to reduce their impact on the time cycle and on delays in the tunneling job.

c. Increased Line Speed. (Investigation of the impact of increasing line speed or cranes.)

Cranes operate with line speeds of about 160 fpm. Hoists use much greater line speeds. An investigation of the impacts on horsepower, torque converters, lagging, rope and cost of increasing line speed to 300 fpm should be undertaken to identify the potential for increasing capacity.

d. Optimized Design. (Development of optimized design for hoisting system in shallow shafts.)

A design for a hoisting system optimized to the requirements for shallow shafts should be developed based on the principles common to cranes and hoists rather than as a modification of designs for other applications.

e. Distribution of Knowledge. (Distribution of knowledge of capabilities of hoisting systems for shallow shafts.)

This task could take any one of several forms. It could be a onetime effort to broadcast the present capabilities of cranes and hoists for shallow shaft hoisting (perhaps the report of the survey of hoisting), or it could be a continuing effort to keep contractors aware of developments in hoisting with emphasis on shallow shafts. It could be expanded to include developments in elevating (continuous methods) as well as hoisting (intermittent).

4. Rubber Tire Haulage

A major concern of the Keystone Workshop panel on rubber tire haulage was the possibility of restricting the use of diesel power in underground construction. It was felt that the lack of diesel power would put a severe limitation on the value of rubber tire vehicles underground and would contribute significantly to increased costs of underground construction. With exception of the ventilation problem, the panel felt there are no technical limitations on rubber tire haulage fulfilling its role in underground construction.

a. Regulations. (Study of government regulations, including ventilation requirements, regarding use of diesel power underground.)

A study of government regulations (federal and state levels), with emphasis on ventilation requirements, and their impact and restrictions on the use of diesel power underground should be initiated. This study, which could be combined with a similar study for rail haulage, should take full advantage of work being done in this area by technical societies and industry groups.

b. Pallet Transport Vehicle. (Development of concept for pallet transport vehicle.)

If a continuous system is used to transport muck away from the heading, an intermittent system will still be required to transport materials and men to the heading. A conventional rail system becomes expensive for the relatively small material flow rates required. A rubber tire system using existing equipment designs is restricted by too little room at the heading for turnaround, too little room for passing in the tunnel and the curved contour of the tunnel floor. One solution to the problems might be a rubber tire vehicle designed specifically for tunneling requirements, including the use of preloaded pallets to maximize the use of the powered vehicles and eliminate the need for passing in the tunnel. Development of a detailed concept for this vehicle would be the first step in its development.

c. Invert Preparation. (Study of requirements and methods for invert preparation for rubber tire haulage.)

An alternative to development of a vehicle for operation on a curved surface would be to flatten the tunnel floor to provide an acceptable roadway. This might be done by filling the invert with muck from the TBM or by use of portable, reusable road base segments made of concrete or steel. The feasibility and economics of these alternatives should be investigated and compared to the develoment of a vehicle to operate on a curved floor. (Even if a flat road surface is prepared, a special vehicle would need to be developed to overcome the turning and passing problems.)

5. Horizontal Belt Conveyors

The major problems with the use of belt conveyors for horizontal transport in tunnels, identified by the Keystone Workshop panel for belt conveyors and through industry interviews, are negotiating curves, extending the conveyor system, transfer points, and obtaining a suitable uniform feed material.

a. Conveyor Belts. (Survey of recent improvements in belt design and fabrication in relation to requirements for tunneling.)

The design and fabrication of conveyor belting have made significant advances in recent years. A survey (in greater detail than the present study) of available belting material and assessment of its ability to meet the severe requirements of tunneling (present and future) would be a first step in overcoming existing problems.

b. Garland Idlers. (Study of application of garland idler principle to short radius curves.)

The use of garland idlers has made it possible to negotiate long radius curves with conventional conveyor belts. A study (theoretical and demonstration) to investigate the application of this principle to shorter radius curves, down to 200 feet, should be initiated.

c. Intermediate Drives. (Investigation of intermediate drives to reduce belt tension for negotiating curves down to 200-foot radius.)

Low belt tension enhances the ability to negotiate curves. Intermediate drives should be investigated as a means of reducing belt tension at curves. Reducing the size of the intermediate drive should also be investigated.

d. Serpentine Belt. (Investigation of Serpentine belt concept for curves of radius greater than 200 feet.)

The Serpentine belt in its present form has the ability to negotiate curves. However, the system is very expensive because of the extreme mobility and flexibility designed into it. The potential use of this belt with a low cost supporting structure designed for tunneling requirements should be investigated. This approach would introduce material transfer points at the curve since the belt would probably be too expensive to use on long, straight runs.

e. Belt Storage. (Development of large belt storage and extension units.)

Belt storage and extension units for up to 500 feet of belt have been operated successfully. There appears to be no technical reason why the capacity of these units could not be increased significantly. These units might provide the solution to the problem of conveyor system extension if used in tunneling. The development of large storage units (up to 5,000 feet of belt) should be investigated, including the addition of new belt and the advancement of the tail pulley. This investigation would include design studies and demonstration of operating units. Demonstration of storage units should be confined to sizes only slightly larger than required by the advance rates achievable.

f. Reliability. (Study of conveyor system reliability to decrease downtime.)

A reliability study, including failure mode and effect, and maintainability analysis would contribute to decreased downtime of the system which represents delay time for the tunneling job since there is no redundancy in the conveyor system. Similar reliability studies would be beneficial to other material transport modes.

g. Installation. (Develoment of concept for low cost installation and removal of conveyor in tunnel.)

The time duration for the use of a conveyor on a tunneling project in a single location is relatively short. Therefore, a rapid, low cost means

of installation and removal is desirable. A study and demonstration of concepts for rapid installation and removal would contribute to the potential use of conveyors.

h. Auxiliary Equipment. (Study problems of transfer points, belt cleaning and lump size control, including in-line crushing.)

Auxiliary equipment such as that used at transfer points (plows, trippers, shock absorbers), belt cleaners, and lump size control equipment (grizzlies, crushers) can become the controlling factor in the conveyor system throughput. Transfer point equipment and belt cleaners are used with the muck car loading conveyor, so studies to improve this equipment should be initiated regardless of the potential of conveyors for horizontal haulage. Lump size control equipment may be required for any continuous system so it could be investigated in a broader program. Other problems at transfer points should also be studied in detail.

i. Cover Belt. (Investigate potential for use of cover belt principle to negotiate curves.)

The principle of the cover belt might offer a solution to negotiating corners if the belt "sandwich" could be rotated 90 degrees before entering the curve. The Loop Belt or Beltavator principle might then carry the material around the curve. Theoretical study and demonstration would be required for this concept.

6. <u>Elevating</u>

The Keystone Workshop panel on elevators recognized the principal problem as the capability of systems to handle a broad mix of materials, particularly to cope with the severe problems related to sticky materials. It was the consensus that this problem is less severe in belt type elevating systems. Proper sizing of materials was recognized as a limiting factor on the use of these systems.

a. Material Discharge. (Investigation of free release of sticky, sluggish material from bucket elevators, muck boxes, skips and belts.)

The discharge or release of sluggish or sticky material from the carrier medium is a problem with muck boxes, skips, bucket elevators and belts. Many attempts have been made to solve this problem, but a systematic, coordinated program has not been undertaken. Such a program should be initiated and carried through the demonstration phase. The causes (including effect of moisture and excessive fines), improved designs, and use of new materials should be included.

b. Bucket Elevator Capacity. (Investigation of methods for increasing height and capacity of bucket elevator.)

With presently available commercial technology bucket elevator capacity and height are limited to less than that required for the far term case. Higher strength chain has been developed but not commercialized, and alternative tension members such as wire rope have been suggested. These

approaches should be investigated as possible means of increasing the height and capacity limitation of bucket elevators.

c. Improved Casing. (Develop improved casing for bucket elevator.)

It has been suggested that a round rather than rectangular casing for bucket elevators might provide better access for maintenance at lower cost. The cost of shaft installations also might be reduced by supporting the load at the top rather than transmitting it to the base through the casing. Improved design to reduce cost should be sought.

d. Knuckle Wheel. (Development of concept for a demonstration of "knuckle" wheel on bucket elevator to improve discharge of materials.)

A "knuckle" wheel concept to bend the buckets further around the head wheel thus providing longer discharge time and more positive discharge action has been suggested as a possible solution to the material discharge problem. This concept should be developed in detail sufficient for a demonstration unit to be built and tested. A simple solution to the discharge problem would enhance the use of bucket elevators in present day tunneling.

e. Intermediate Drive. (Development of concept for intermediate drive to increase height limitation of bucket elevator.)

It has been suggested that an intermediate drive at about the midpoint height of a bucket elevator would reduce the deadweight on the tension members thus permitting the height to be extended. A general concept exists but it has not been developed to the fabrication stage. This concept should be developed and tested.

f. Bucket Elevator Demonstration. (Demonstration on the job of improved bucket elevator concepts developed.)

Concepts for increasing height and capacity which appear to offer the best solutions after design and test should be demonstrated under on-the-job conditions by installation and use at an on-going job.

g. Variable Materials. (Investigation of problems associated with handling highly variable material in bucket elevator.)

The variability of the characteristics of muck has been identified as a major problem in the use of continuous elevating systems. This problem should be investigated to determine the range of muck characteristics (including frequency of oversize pieces), the impact on the handling equipment, and potential corrective actions.

h. Beltavator Demonstration. (Demonstration of present Beltavator at height of interest for tunneling and at increased speeds.)

A Beltavator demonstration unit approximately 45 feet in height exists as an aboveground, free standing unit. Demonstrations should be run on this unit with typical "problem" mucks. The use of increased speeds should also

be tested. If successful, a demonstration unit should be constructed in a shaft at an active jobsite and tests run under job conditions.

i. High Capacity Beltavator. (Investigation of lateral stiffening and increased strength of belt to increase capacity of Beltavator.)

It has been suggested that the capacity of the present Beltavator is limited by the lateral stiffness of the belts. An investigation should be initiated to determine the potential for increased capacity by increasing lateral stiffness and longitudinal strength of the belt. If this approach appears favorable, demonstration belt should be fabricated and tested.

j. Improved Beltavator Demonstration. (Demonstration of improved models of Beltavator.)

As improved (higher capacity and greater height) Beltavators are demonstrated in pilot tests, they should be constructed in a shaft and run under job conditions.

k. Vertical Flexowall. (Study of vertical conveying with Flexowall concept.)

A study should be made of the potential for vertical conveying with the Flexowall concept. Present Flexowall systems can convey on inclines up to 80 degrees but capacity decreases rapidly for inclines greater than 45 degrees. Special cleat designs and the use of a cover belt to increase capacity for vertical transport should be investigated.

l. Flexowall Demonstration. (Demonstration of Flexowall concepts for vertical conveying.)

As potentially favorable vertical Flexowall concepts are developed through the prototype test, they should be installed in a shaft at an active job for demonstration under job conditions.

m. Installation. (Develop concepts for low costs rapid installation and removal of bucket elevator, Beltavator, and Flexowall.)

If concepts for bucket elevators, Beltavators and Flexowall are demonstrated to be practical for future elevating of muck, the designs should be reviewed in an attempt to reduce the time required and cost for installation and removal of the systems.

n. High Capacity Serpentix. (Investigate the potential for increased capacity of Serpentix conveyors.)

The capacity of the Serpentix conveyor is limited by the travel speed of the chain driven Serpentix belt. The potential for increasing the capacity of a spiral Serpentix by increasing speed could be investigated.

7. Slurry Transport

The Keystone Workshop panel for slurry pipeline transport stated that the experience of the panel indicates very low unit transportation costs for slurry pipelines. The panel felt that recent development of better feeders, pumps, pipe and separators for other applications and further development of engineering data and equipment will permit increased utilization of hydraulic transportation for tunnel construction.

a. Engineering Data. (Development of improved engineering data for hydraulic transport.)

Considerable engineering data have been developed for slurry transport of bulk materials. Most of these data are for small particle size with narrow distribution range. Some data have been developed for large particles but much of it is held proprietary by commercial organizations. A major impediment to the design of slurry systems for muck transport is the lack of data in the range of particle size distributions, material densities, and slurry concentrations of interest for tunneling. Work has been initiated recently at Government laboratories to develop data in these ranges but the principal emphasis is on the transport of coal.

b. Slurry Pumps. (Development of improved slurry pumps in range of interest for tunneling.)

Slurry pumps are felt to be adequate for present needs but improvement may be needed for future requirements. Studies leading to optimum pump designs for the conditions and ranges of interest for tunneling should be initiated.

c. Handling-Feeding System. (Development of an integrated system for muck handling between the mole and the pipeline.)

Relatively little attention has been given to the handling and processing of the muck between the mole and the pipeline. Studies leading to an integrated handling-feeding system (separating, crushing, feeding) should be initiated.

d. Solids Separation. (Development of integrated optimum system for separation of solids from slurry.)

One of the problems confronting the application of slurry transport to muck removal is the separation of the solids from the slurry. Although the separation of suspended solids from slurries has been practiced for many years for cleanup of industrial and municipal wastewaters, and the separation of muck from the slurry resulting from hydraulic excavation in St. Peter sandstone has been successfully demonstrated, techniques for accomplishing this separation satisfactorily and without unacceptable cost for the range of muck materials which might be encountered have not been demonstrated. The development of an integrated system for solids-fluid separation suitable for a wide variety of muck types would be required before general acceptance of this transport mode.

e. Instrumentation. (Development of improved instrumentation for slurry pipeline.)

Efficient operation of a slurry transport system requires on-line measurements. Instruments with reliability and life satisfactory for tunnel driving environments and for slurry measurements are not available. The development of these instruments would be required before general acceptance of the transport mode.

f. System Extension. (Development of improved method of slurry pipeline extension to reduce delay time.)

The slurry system developed for application to coal mine face haulage uses large (10 inch) diameter hoses to gain flexibility for extension and retraction of the system. Use is made of side drifts to store the hose loops when not fully extended. The practicality of hose or other means of extension in a tunnel where side drifts are not available should be evaluated. An extension system suitable for in-tunnel use would need to be demonstrated before general acceptance of slurry transport for muck removal.

g. Wear. (Investigation of wear and erosion of equipment and pipe when handling tunnel muck.)

Inadequate data are available on the wear and erosion of pipeline and equipment when handling slurry with the characeristics produced by various tunnel mucks and large particle sizes. Tests should be conducted with muck materials in the particle size and flow velocity ranges of interest to muck transport. Cost savings could be realized by cooperative programs with existing slurry research efforts.

8. Pneumatic Transport

The Keystone Workshop panel on pneumatic pipeline concluded that it can be anticipated that high power consumption in a pneumatic conveying system is inherent. It further concluded that continued improvements in metallurgy, design of components and maintenance will result in less abrasive wear and more acceptable running costs.

a. Demonstration of Current Equipment. (Demonstration of pneumatic transport of tunnel muck at maximum rate of available feeder equipment.)

Current pneumatic feeder equipment is designed for capacities up to 200 tph. This equipment should be tested up to its full capacity using muck-like material as the feed. Emphasis should be on elevating up to 300 feet.

b. High Capacity Feeder. (Development of feeder for up to 400 tph system.)

A high capacity feeder (up to 400 tph) should be developed. A design for this feeder has been initiated by industry.

c. Handling and Feeder System. (Development of integrated handling and feeder system for high capacity.)

Following successful demonstration of a high capacity feeder, an integrated muck preparation and feeder system should be designed and demonstrated for high capacities (up to 400 tph).

d. High Capacity Demonstration. (Demonstration of pneumatic transport of tunnel muck at rate of 400 tph.)

Pneumatic transport of tunnel muck at rates up to 400 tph should be demonstrated. Emphasis should be on elevating up to 300 feet.

e. Discharge Separation System. (Development of integrated discharge separation system.)

The separation of the solids from the air stream at discharge is not anticipated to be a major problem, except when sticky materials are involved. However, development of integrated discharge separation systems would need to keep pace with the development of higher capacity feeders. The severity of problems with dust, noise and sticky materials would be determined during these studies.

f. Wear. (Investigation of wear for all materials with potential for pipe and fittings.)

Excessive wear of pipe and fittings is sometimes a problem with pneumatic transport. Tests to determine wear characteristics of some materials when transporting rock have been initiated. Longer term tests to evaluate all materials with potential would need to be conducted to develop adequate engineering data.

g. Dense Phase Transport. (Investigation of dense phase pneumatic transport.)

High pressure (or dense phase) closed loop pneumatic systems with pressure drops less than 10 psi have been suggested as a means of reducing particle velocity and pipe wear while extending the practical distance for material transport. No work is being done in this area at the present time and very little, if any, has been done in the past. This effort should begin with theoretical analysis and proceed to small scale test and demonstration.

h. Sticky Materials. (Investigation of problems in handling sticky and wet materials.)

The problems associated with handling sticky and wet materials in pneumatic systems should be carefully evaluated. This effort should precede the development of high capacity systems for muck handling.

MATERIAL HANDLING R&D PROGRAM

A material handling research, development, test and demonstration program adopted to assure that the material transport capability of the

tunneling system will keep ahead of the material flow requirements should be based on the following goals:

a. To offer early solutions to the most imminent problems.

b. To offer the greatest probability of problem solution at minimum cost.

c. To offer solutions to the most serious problems.

d. To offer solutions to problems anticipated for the far term period as well as the near term.

e. To take maximum advantage of ongoing related R&D efforts so as to avoid duplication of effort.

f. To attack those problems which appear least likely to be solved in a timely manner by manufacturers or contractors.

For example, early attention in the program should be given to problems which presently delay projects or are anticipated to cause delays in the near future. These include problems with lifting through the shaft, problems associated with rail haulage, and material handling problems associated with installation of initial ground support. Early solutions at minimum cost, at least for the near term, can often be found by upgrading the systems presently in use rather than embarking on time consuming and costly development of new systems or adaptation of systems from other applications which would require major modifications or extensions of system capability.

Emphasis should be placed on the most serious problems, for example, those that become progressively worse as the material transport requirements increase and those that completely shut down the job. Potential solutions for problems in the near term should be evaluated for their potential to meet the requirements of the far term. A material transport concept that may look good for the near term but would require major extrapolation beyond its demonstrated capability to meet the requirements of the far term should receive less attention than one that looks equally good for the near term and requires only minor extrapolation for the far term.

A concept that is being investigated in ongoing R&D programs is a less likely candidate for funding than a concept that offers an equally attractive solution but is unfunded. The ongoing R&D programs should be systematically monitored and the results evaluated in relation to the problem of concern.

In view of the uncertainties inherent in research and development efforts, it is prudent to pursue more than one concept as a solution to a specific problem, particularly in the early phase of a program. The results obtained from early phase efforts will provide a basis for reduction, expansion, or elimination of future program tasks. It may be desirable to add new tasks as the program progresses. If two or more concepts appear equally attractive throughout the development program, alternatives will be available for contractor choice. Flexibility in the program should be maintained, keeping in mind that the program objectives are to assure that material

handling does not become the controlling factor on the rate of face advance and to reduce material handling cost; not the development of material handling systems per se.

Because of the wide variability of conditions of tunneling projects, there may be special situations in which a solution selected for the general situation is not the best. Other concepts which appear to be better solutions for these special situations should be developed if the extent of potential application justifies the cost of development.

With the above objectives in mind, an assessment was made of the potential R&D items of the preceding section. A list of program tasks with priorities and estimated funding was developed as displayed in Table 79. In this table the item numbers correspond to the subsection designations of the preceding section. The costs indicated are order-of-magnitude, based on a preliminary appraisal of the scope of work implied by the preceding item-by-item discussion of the potential tasks.

First priority for the near term is given to continuous systems for elevating, to problems related to rail haulage, and to ground support installation. Continuous systems are felt to be preferred over intermittent systems for lifting muck in the far term. The Beltavator principle has been demonstrated but tests have not been made using typical tunnel muck, nor has the system been demonstrated in a tunneling environment, although it appears to have good potential for this application. The Flexowall system has been proven at inclines up to 70 degrees but has not been demonstrated for vertical elevating. If it is proven for vertical elevating its application for muck elevating would be enhanced. The bucket elevator has been demonstrated in the tunneling environment. The major problem is indicated to be discharge of sticky material. The major problems with rail haulage are ventilation, system reliability and extension of quality track.

The technical feasibility of transporting rock with a pneumatic system has been demonstrated. Before larger scale tests are conducted the question of handling, discharging and recovering sticky material should be addressed.

Hoisting (by crane and hoist) is well established in the tunneling industry. There is some feeling that the full capability of these systems is not realized or used by the industry.

The use of conveyors for horizontal transport of muck depends on a solution to the problem of curves and on the development of a special rubber tire vehicle for incoming material transport. Garland idlers may offer a solution to the curve problem and invert preparation is a factor in development of a rubber tire vehicle.

Unless satisfactory, low cost methods are available for separation of the solids from the slurry, much of the appeal of hydraulic transport of muck is lost.

The intermediate term and far term tasks continue the development of systems (assuming earlier tasks produce favorable results) through full scale demonstrations on a tunneling project. Slurry transport is given a low

TABLE 79. MATERIAL HANDLING R&D PROGRAM TASKS

(Cost Estimated in Thousands of 1978 Dollars)

Item Number	Task	Priority		
		1	2	3
	NEAR TERM (1-3 Years)			
6h	Beltavator Demonstration	350		
6k,1	Vertical Flexowall	350		
6ad,2e	Material Discharge	600		
2b,4a	Regulations & Ventilation	250		
2h,a,c	Rail System Reliability	275		
1b	Initial Ground Support	125		
2i	Track Laying	80		
8h	Sticky Material in Pneumatic System		150	
1h	Market Identification		130	
1g	Tunnel Alignment		100	
3a,b,2f	Survey of Hoisting		250	
5b	Garland Idlers		400	
4c	Invert Preparation		75	
8e	Pneumatic Discharge System			150
2j	Rail System Wear			100
6g	Material Variability in Elevating			80
5a	Conveyor Belt Design			50
3c	Crane Line Speed			50
7d	Slurry Solids Separation			500
	TOTAL NEAR TERM	2,030	1,105	930
	INTERMEDIATE TERM (4-10 years)			
3d	Optimum Hoisting System	150		
3e	Distribution of Hoisting Knowledge	200		
2g	Muck Car Loading	250		
6b,e	Bucket Elevator Capacity	900		
6i	Beltavator Capacity	250		
5e	Belt Storage & Extension	300		
5c	Belt Intermediate Drive	150		
4b	Pallet Transport Vehicle	100		
6j	Beltavator (Improved) Demonstration		400	
6c	Bucket Elevator Casing		50	
6f	Bucket Elevator (Improved) Demonstration		400	
2k	Rail System Safety		50	
5g	Conveyor Installation		300	
5d	Serpentine Belt for Curves		500	
1c	Breaker-Feeder		900	
1d	Wear in Pneumatic System		900	
2d	Locomotive Design			100
6m	Elevator Installation			180
8a	Pneumatic Demonstration			300
1f	Material Transport Handbook			300
5h	Conveyor Auxiliary Equipment			300
7a	Slurry Engineering Data			300
7f	Slurry Pipeline Extension			900
6n	High Speed Serpentix			500
	TOTAL INTERMEDIATE TERM	2,300	3,000	3,230
	FAR TERM (More than 10 years)			
5f	Conveyor System Reliability	100		
8b	Pneumatic Feeder (High Capacity)	200		
8c	Pneumatic Handling - Feeder System (High Capacity)	150		
8d	Pneumatic Demonstration (High Capacity)	600		
7g	Wear in Slurry System		900	
7c	Slurry Handling - Feeder System		400	
7e	Slurry Instrumentation		400	
7b	Slurry Pumps		900	
1e	Design Review			300
5i	Cover Belt for Curves			400
21	Rail on Steep Grades			400
	Pallet Vehicle Demonstration	600		
	TOTAL FAR TERM	1,650	2,500	1,100
	TOTAL PROGRAM	5,980	6,605	5,260

priority because several programs to develop basic engineering data are in progress, and the problems of system extension and solids separation should be solved before considering the slurry system as a viable solution for muck transport in general.

In summary, the program gives major emphasis to lifting muck by continuous mechanical methods and to horizontal transport of muck by upgraded rail haulage. The full potential of intermittent hoisting should be developed particularly for the intermediate term. Investigation of belt conveyors based on recently developed belt technology is recommended as a backup system to rail haulage. Monitoring and assessment of the results from ongoing development programs for pipeline systems are recommended and better definition of the feed and discharge end problems for transport of tunnel muck should be developed.

Cost estimates for first, second, and third priority tasks are cast in the form of a schedule in Figure 80. Reallocation between tasks is anticipated as new data is developed from the early phase tasks.

APPROACH TO R&D PROGRAM

A major objective of the approach developed for execution of a program for improvement of material handling in urban tunneling should be to obtain maximum participation of equipment manufacturers and tunnel contractors. However, it should be recognized that the incentive for financial participation of manufacturers and contractors is determined by their analysis of the potential return on investment. For a relatively small and uncertain market with little growth potential, the incentive is small for a manufacturer to invest in innovation or product modification to meet the needs of that market. The incentive for a contractor to make the investment and take the risk associated with the use of unproven equipment is usually limited to the return he anticipates from one or two jobs since successful innovations are quickly recognized throughout the industry. The major incentive for improving material handling methods for tunneling lies with the owner, that is, the public. Therefore, the major cost of these improvements must be borne by the public.

To obtain the desired participation by manufacturers and contractors it will be necessary to develop working relationships such that the financial commitment and risk to the manufacturers and contractors are commensurate with their incentives.

One arrangement which might be used for on-the-job demonstration of new equipment would be to install the new equipment in parallel with conventional equipment. In the event of malfunction of the new equipment, the conventional equipment could be used without job interruption. The cost of the new equipment installation and operation would be paid by public funding with possible participation (by the manufacturer) for capital cost of equipment. The contractual agreement would minimize the risk to the manufacturer and contractor.

TABLE 80. MATERIAL HANDLING R&D PROGRAM SCHEDULE

(Cost Estimated in Thousands of 1978 Dollars)

PROGRAM ELEMENT	Estimated Budget by Year													
	Year after Program Initiation													
	Near Term			Intermediate Term							Far Term			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Near Term														
First Priority	1,000	1,000												
Second Priority		400	600	100										
Third Priority			500	400										
Intermediate Term														
First Priority			400	700	700	500								
Second Priority				400	600	800	900	700	500					
Third Priority							400	600	800	1,200	200			
Far Term														
First Priority										300	400	600	400	
Second Priority											800	900	800	
Third Priority													300	800
Total by Year	1,000	1,400	1,500	1,600	1,300	1,300	1,300	1,300	1,300	1,500	1,400	1,500	1,500	800

Another possibility would be to establish the infrastructure for system testing at an existing government facility so systems could be tested in a simulated tunneling environment before they were sufficiently proven for on-the-job demonstration.

Urban mass transit tunneling represents only a portion of the possible applications of material handling systems developed for its needs. When other potential applications can be identified, shared funding of development efforts should be sought.

Many complex questions are involved in government-industry-contractor team efforts. These questions should be investigated early in the R&D program to identify satisfactory arrangements for maximum participation by manufacturers and contractors.

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APPENDIX A

THE COST MODEL

The tunneling cost model is based on a cost estimating procedure used by professional tunnel construction estimators for the preparation of competitive bids for contractors. With the exception of some indirect costs which do not change with alternative material handling systems, the model includes all costs for excavation and initial ground support of a dual-tube tunnel primarily in medium or hard rock. It does not include costs for:

a. Construction of stations or terminals.

b. Construction of access or vent shafts unless constructed solely for use by the material handling system.

c. Construction of adits, connecting links, pockets or rooms unless directly related to the material handling system.

d. Installation of final lining, subsequent to excavation and initial support.

The cost model assembles a total job cost from a description of the job (Figure B-1), a schedule (Figure B-2) and primary cost elements such as labor rates, purchase cost of equipment, supplies and materials, equipment salvage values, and labor hours expended, and indirect costs such as office expenses, insurance and taxes. Figure B-3 shows the principal cost categories and the process of assembly into the total job cost. The number "1" in the upper left corner of several boxes indicates that this is information appearing on the "Total Job Cost Summary" sheet, page 1 of the estimate. The other numbers, from 3 1 to 10 2, indicate the type of table which contains the information on subsequent pages in the estimate. These table identification numbers appear in the lower right corner of the estimate sheets produced by the computer program.

Project costs have been divided into costs for materials handling and costs for non-materials-handling functions (excavation and installation of initial ground support). Within each of these divisions are three main subdivisions:

1. Direct Costs

2. Plant and Equipment

3. Indirect Costs

Direct costs include the cost of

a. labor crews including equipment operators for excavation and installation of ground support (Sheet 1 1) and materials handling (Sheet 1 2)

b. crews for Saturday maintenance of excavation, installation and materials handling equipment (Sheet 4 1)

c. repair labor, and parts and supplies (including fuel and electric power) for operation and maintenance of excavation, installation and materials handling equipment during the normal work week (Sheet 2 1)

d. the crew for removal of the fanline after completion of excavation (Sheet 1 3)

e. the development excavation (Sheet 5 1) needed for installation and startup of the mole and materials handling system.

The development excavation costs include the costs of

a. the drill-and-shoot excavation crews (Sheet 1 4)

b. the shaft operation crews during development excavation (Sheet 1 5)

c. the cost of equipment repair labor (Sheet 2 1)

d. the cost of parts and supplies (including fuel and electric power) for equipment operation and maintenance (Sheet 2 1)

e. the cost of muck disposal by contracted haulage (Sheet 5 1).

Daily crew costs are developed (Sheets 1 1 through 1 5) from shift rates for each job position in a crew and the number of man-shifts worked per day by that position. The shift rates are developed from base hourly rates with additional time at overtime rates added as required (illustrated by Figure B-4b).

The daily repair labor costs, and parts and supplies costs for equipment operation and maintenance are derived (Sheets 2 1 through 2 3) from hourly costs for each item of equipment and the number of hours per day that the equipment item operates.

The Direct Cost Summary (Sheet 2 1) collects and sums the above costs. In addition, costs for purchase of ground support materials, maintenance tools and supplies, general small tools and supplies, incidental overtime, and subcontract disposal of muck are entered directly on the Direct Cost Summary Sheet. Detail sheets that support these and other cost items are illustrated in Figures B-5a, b, c.

The Plant and Equipment Cost Summary (Sheet 6 0), accumulates and totals the portion of the equipment and facilities purchase costs which is charged to the job, the shipping charges for moving equipment to and away from the job, and labor costs for erection and removal of equipment and facilities. These are developed on detail sheets for

a. Buildings and Yard (6 1)

b. Utilities (6 2 and 6 3)

c. Lifting Equipment (6 4)

d. Rubber Tired Haulage Equipment (6 5)

e. Horizontal Transport Equipment (6 6)

f. Rock Drilling Equipment (6 7)

g. Tunnel Boring Machine (6 8)

h. Trailing Equipment behind the mole (6 9)

i. General Vehicles and Equipment 6 10)

The portion of the purchase cost for an equipment item which is charged to the job is determined by subtracting a salvage value from the purchase cost. The salvage value is obtained by applying to the purchase cost a salvage percentage based on the AGC Contractors' Equipment Manual (1) or by assigning a judgmental percentage.

Indirect costs summarized on the Total Job Cost Summary (Sheet 1) include Overhead Labor (7 1), Miscellaneous Expense (9 1), and Insurance and Taxes (10 1 and 10 2). Costs accumulated on these sheets are based on computation sheets illustrated in Figures B-6a, b, c, d,.

H & N BCNT   PES   JUL 13 1977
AUG 1 1977

LENGTH OF TUNNEL	:	2 each @ 10,000 feet = 20,000 feet
ACCESS SHAFT	:	30 feet diameter x 100 foot deep
EXCAVATION	:	1200 hp mole. Penetration 2 IPM Production 118.8 FPD Utilization 52% Availability 87%
SUPPORTS	:	270° sets, 4000TF @ 5' c-c = 800ea Epoxy bolts 4000TF @ 4' c-c x 8ea/row Expansion bolts 12,000TF @ 4' c-c x 6ea/row
MATERIALS HANDLING		
HORIZONTAL	:	Balanced floor with car shifter 25T x 180 hp locomotive pulling six 20CY cars per train 1 loco and 2 trains for first 3000TF 2 " 3 " " next 7000TF Availability 94%
VERTICAL	:	70T crane lifting 20CY lift-off boxes at 350 FPM with single part line.

SUMMARY OF ESTIMATE

PROJECT H & N BCNT ESTIMATOR PES DATE JUL 13 1977 JUL 26 1977 M 02

				HOURS	
PRODUCTION	MOLING	19,440' ÷ 10FPH		1944	—
					—
					—
	RESET	19,440' ÷ 6' PER STROKE = 3,240 STROKES x 2 MIN		108	2,052
DELAYS	ROCK SUPPORT BOLTS	NO DELAY	—	—	—
	SETS	800 ea x 30 MIN (ALLOWS 1 HR TO SET RING)	400	400	—
	MATERIALS HANDLING	CHANGE TRAINS	—		—
		DERAILS 0.001 HR/TF (10 MIN/WD)	19	—	—
		HOISTING .005 " (35 ")	97	–	—
			–	116	—
	VENTILATION	.002 HR/TF		39	—
	POWER ADD CABLE	18 ea x 3 HRS	54	—	—
	OUTAGES	1 ea x 8 HRS	8	62	—
	CUTTERS	5% OF MOLING TIME (35 MIN/WD)		97	—
	EQUIPMENT REPAIRS MOLE	20% "	389	—	—
	MATERIALS HANDLING	5% " (TRAILING EQUIPMENT)	97	—	—
	DRILLS	3% "	58	—	—
	OTHER	1% "	19	563	—
	SHIFT CHANGE	.005 HR/TF (57 MIN/WD)		156	—
	MISCELLANEOUS	STARTUPS 10 WD + 7 WD, CURVES 2 WD = 19 WD x 24 HR		456	1,889
				TOTAL SCHEDULED TIME	3,941

SCHEDULED 24 HR/WD PENETRATION 10 FPH MOLE UTILIZATION 49 %

ELAPSED TIME 164 WD MOLING TIME 11.8 HR/WD MOLE AVAILABILITY 88 %

PRODUCTION 118.5 FPD MATERIAL HANDLING SYSTEM AVAILABILITY 95 %

MOLE EXCAVATION PROGRESS PAGE 4

FIGURE B-1. JOB DESCRIPTION

H & N BCNT

PES

JUN 13 1977

JUL 13 1977

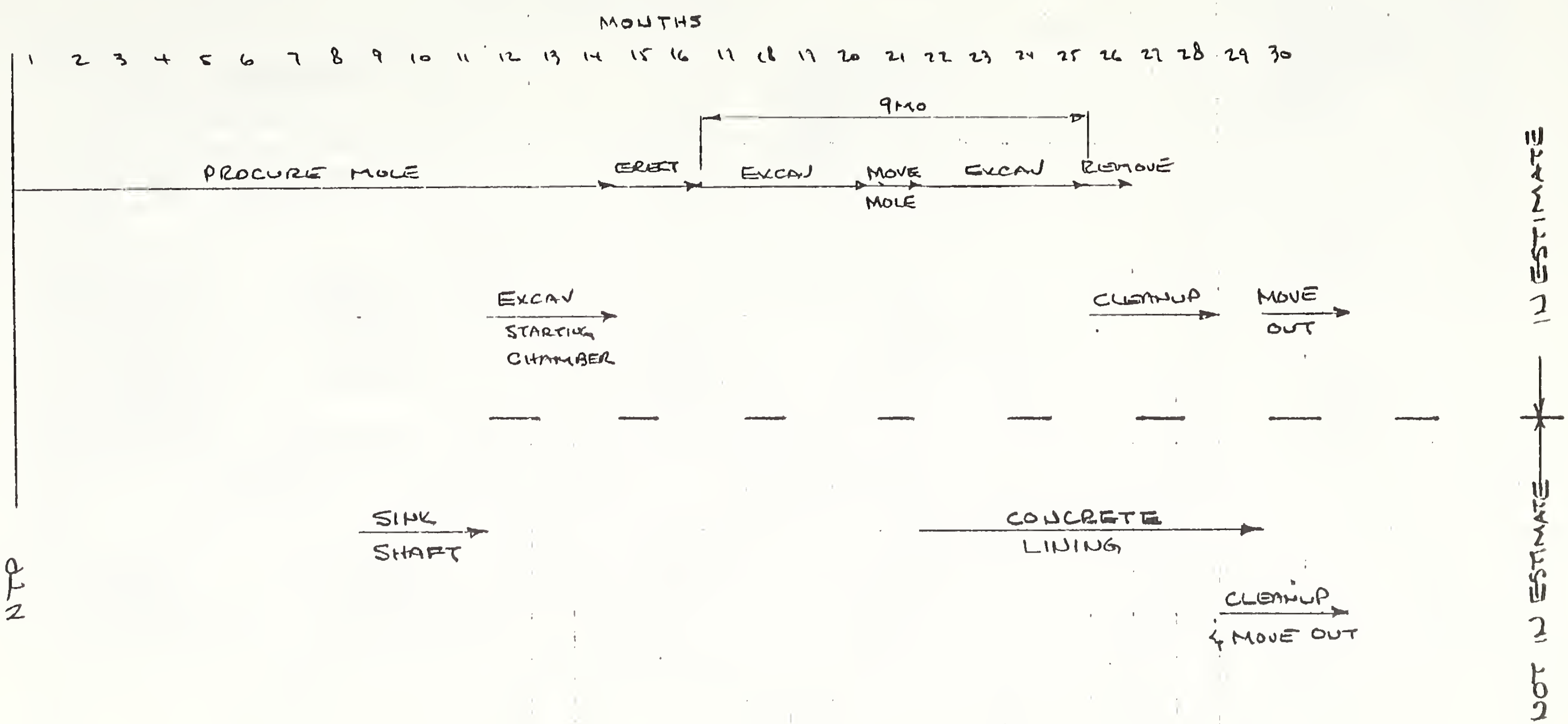

FIGURE B-2. JOB SCHEDULE

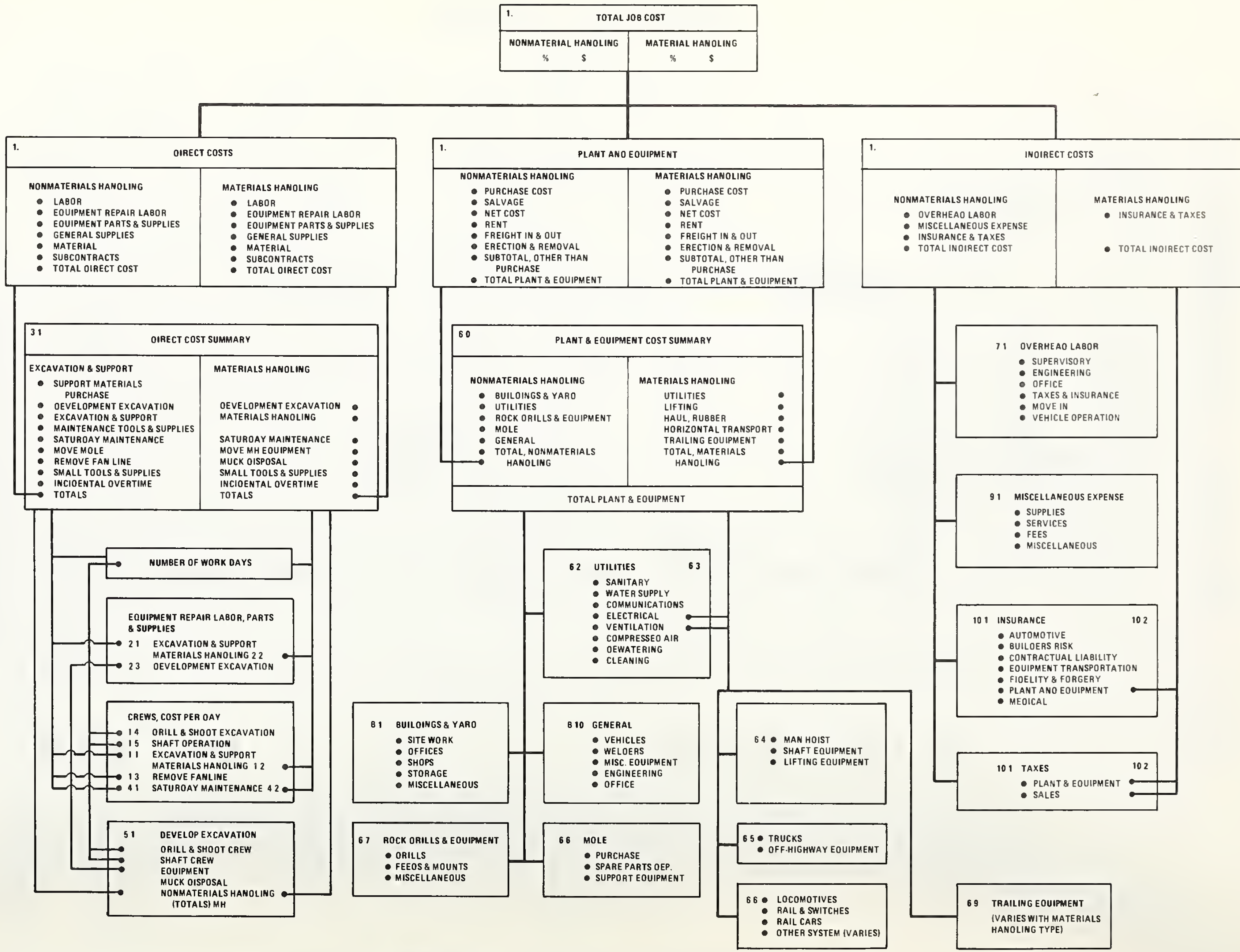

FIGURE B-3. PRINCIPAL COST CATEGORIES

PROJECT ______________ ESTIMATOR DES JUN 13 1977 JUL 13 1977

Source of hourly rate Washington D.C. escalated to 1-1-78

H & N BCNT

CLASSIFICATION	HOURLY RATE	SHIFT RATE SURF	SHIFT RATE SHAFT	SHIFT RATE UNDG
Laborers		(3)	(2)	(1)
Shifter B.G. Foreman	13.20		–	135
Miner, Nipper	11.96		–	123
Chucktender, Signalman	11.16		106	114
Brakie, Bullgang	10.81		103	107
Foreman	11.01	88		
Laborer	10.44	84		
Electricians				
Foreman	26.08	209	209	209
Journeyman	23.81	190	190	190
Teamsters	9.42	75	–	–

CLASSIFICATION	HOURLY RATE	SHIFT RATE SURF	SHIFT RATE SHAFT	SHIFT RATE UNDG
Operators		(3)	(2)	(1)
1 >35T Crane, Hoist	14.68	117	140	–
2 Mole, FEL >3½ CY, Mult. Conv	14.34	115	–	147
3 FEL 2¾ - 3½ CY	14.15	113	–	–
4 Compressor, Pumps	13.92	111	132	143
5 FEL < 2¾ CY	13.83	111	–	–
6 Mechanic	13.83	111	131	142
7 Motorman, Conveyor	13.60	109	129	139
8 Dozer	13.60	109	–	–
9 Oiler	11.88	95	113	122

FIGURE B-4a. HOURLY RATES, STRAIGHT TIME

R JUL 13 1977

JUN 13 1977

PROJECT [illegible]

ESTIMATOR DES

CREW	Shifts Worked per Day	Change at Heading	Work Through Lunch
1 Heading	3	Yes	Yes
2 Shaft	3	No	Yes
3 Surface + Electricians	1	No	No
4			
5			
6			

HOURS	1		2		3		4		5		6	
	WORK	PAY	WORK	PAY	WORK	PAY	WORK	PAY	WORK	PAY	WORK	PAY
Straight Time	7½	8	7½	8	8	8						
Overtime - Normal	½	¾	½	¾								
Lunch	½	¾	½	¾								
Travel	½	¾	-	-								
Other												
TOTALS	9	10¼	8½	9½	8	8						

FIGURE B-4b. OVERTIME RATE CALCULATIONS

R JUL 13 1977

PROJECT H & N BCNT ESTIMATOR PES BID DATE JUN 13 1977

FACTORS : LABOR 13.83/10.00 = 1.38. PARTS 220/188 = 1.17. POL .60/.50 = 1.20. POWER .06/.03 = 2.00. TIRES 1.50/1.25 = 1.20.

	DESCRIPTION	LABOR	P & S	PARTS	POL	P/T
AIR POWERED	Rock Bolt Drills	.60	1.00	.76	.18	-
	Impact Wrench	.40	.50	.35	.12	-
CONCRETE						
DIESEL POWERED	Crane, Hyd 10T	3.30	5.40	3.50	1.32	.60
	" Crawler 125T	9.70	17.70	10.65	7.08	-
	Locomotive					
	" 25T 180hp	3.30	8.90	3.74	5.20	-
	" 30T 270hp	4.10	12.30	4.45	7.80	-
	" 40T 370hp	4.80	16.00	5.25	10.70	-
	" 45T 580hp	6.90	25.60	8.80	16.80	
	Train, Supply 5T	4.00	10.90	2.90	7.40	.60
	Welder 200A	1.10	5.30	1.30	3.90	.10

	DESCRIPTION	LABOR	P & S	PARTS	POL	P/T
ELECTRICALLY POWERED	Compressor 1200 CFM	1.00	10.20	1.05	1.20	8.00
	Pump 400G/60' 13 hp	.20	.80	.30	.10	.40
	" 700G/100' 30hp	.90	1.60	.47	.12	1.00
	Alimak Elevator U 500	2.10	1.20	.58	.24	.40
	Microdyne Dust Coll. 7hp	.40	.80	.18	.06	.60
	Vent Fan 50hp 20,000 CFM	.10	1.70	.10	.07	1.50
	75hp 30,000 "	.20	2.60	.23	.08	2.26
	100hp 40,000 "	.30	3.50	.35	.13	2.98
	125hp 60,000 "	.40	4.40	.47	.18	3.70
	200hp 130,000 "	.60	7.20	.80	.20	6.00
	Hoist 500HP	9.10	37.10	10.80	2.30	24.00
	Trailing Conveyor w/Shifter	-	14.00	10.65	.60	2.80
	Welder Shop 300A	.30	1.90	.12	.30	1.50
SHOTCRETE						
UNPOWERED	Flat Car 30T	.20	.30	.25	.05	-
	Man Car 30 man	.60	.40	.30	.10	-
	Muck Car 15 CY	.70	.40	.20	.12	-
	" " 25 CY	1.10	.70	.47	.24	-
	20 CY	.90	.60	.38	.18	-
OTHER						

EQUIPMENT COST PER OPERATED HOUR

34

FIGURE B-5a. SUPPORTING DATA

BY .... DATE .... SUBJECT PLUG PRICES .... SHEET NO .... OF ....

CHKD. BY .... DATE .... JOB NO. 35

R JUL 13 1977

H & N BCNT

PES

AGGREGATE SAND	— / T.	MUCK HAUL	3.00 /CY
COARSE	— / T.	PIPE	— /LF
CEMENT BAG	— /CWT		— /LF
BULK	— /CWT		— /LF
CONCRETE TRANSIT MIX	— /CY	POWER	.06 /KWH
ADDITIVE	— /CY	PRECAST CONCRETE	— /CY
BLASTING CAPS	— /ea	REBAR PINS	.17 / #
POWDER	— / #	RIPRAP	— /CY
FANLINE ___"ø	* /FT	ROCK BOLTS & ACCESSORIES	
FORMS LUMBER	— /MBF	EXPANSION BOLTS	.80/LF
PLYFORM	— /SF	EPOXY BOLTS	2.00/LF
TUNNEL	— /SF	PANS	— / #
TRAVELER	— /ea	BEARING PLATES	— / #
LAGGING & BLOCKING	.22 /MBF	STEEL PILING	— /Ton
MISCELLANEOUS METAL		STEEL SETS	.33 / #
CHAIN LINK FABRIC	.15/SF	TIES STEEL	10.00/ea
MOLE CUTTERS	2.50/CY	WATERSTOP	— /LF

FANLINE	30"ø	8.50/LF
	48"ø	13.50/LF
	60"ø	17.00/LF
	84"ø	21.10/LF

PLUG PRICES

FIGURE B-5b. SUPPORTING DATA

H & N BCNT PES

R JUL 13 1977
JUN 13 1977

SETS 4000TF ÷ 5' C-C = 800 ea + 10% = 880 ea
USE 3 PIECE 270° EXPANDED SETS OF W 6 × 20
92'/ea × 20#/FT × 1.2 (TIE RODS, PIPE COLLAR BRACES & BUTT PLS)
= 2200#/ea × 880 = 1,936,000# @ $.33/# = $638,900

LAGGING 30 ea 3" × 6" × 5'-0" PER SET = 225 BF/SET × 880 ea × $.22/BF = 43,600

PINS #11 REBAR × 2½' × 4 ea/SET × 880 ea = 8800 LF × 5.05#/FT × $.17/# = 7,600

WEDGES, ETC 4,000

ROCK BOLTS
EPOXY 4000 TF ÷ 4' C-C = 1000 ROWS @ 8 ea/ROW × 1.10 = 8,800 ea × 6' × $2.00/FT = 105,600
EXPANSION 12,000 TF " = 3000 " " 6 ea/ " " " = 19,800 ea × 6' × .80/FT = 95,000

CHAIN LINK FABRIC 4,000 TF × 6' WIDE × 1.10 = 26,400 SF × .15/SF = 4,000

TOTAL $898,700

SUPPLIES BITS & STEEL 28,600' DRILLING × .15 = $4,300

PURCHASE SUPPORT MATERIALS & SUPPLIES

36

FIGURE B-5c. SUPPORTING DATA

PROJECT H & N BCNT ESTIMATOR DES DATE JUN 13 1977 JUL 13 1977 I 01

DESCRIPTION	NO.	MAN-MONTHS EACH	MAN-MONTHS TOTAL	RATE	COST	VEH
SUPERVISORY						
PROJECT MANAGER	1		28	3500	98,000	S
GENERAL SUPERINTENDENT						
AREA SUPT.						
TUNNEL SUPT.	1		18	3,100	56,000	P
SHIFT SUPT.						
WALKERS	3	10	30	2,700	81,000	–
EQUIPMENT SUPT.	1		19	3,200	61,000	P
MASTER MECHANIC						
ELECTRICAL SUPT.						
EXCAVATION SUPT.						
CONCRETE SUPT.						
CARPENTER SUPT.						
TOTAL SUPERVISORY			95		296,000	3
SUMMARY						
SUPERVISORY	7		95		296,000	3
ENGINEERING	9		136		266,000	3
OFFICE	7		117		177,000	1
TOTAL LABOR	23		348		739,000	7
TAXES & INSURANCE	19%				140,000	
TOTAL LABOR CHARGE					879,000	
MOVE IN			7ea	4000	28,000	
VEHICLE OPERATION			145MO	200	29,000	
TOTAL OVERHEAD LABOR					936,000	

DESCRIPTION	NO.	MAN-MONTHS EACH	MAN-MONTHS TOTAL	RATE	COST	VEH
ENGINEERING						
PROJECT ENGINEER	1		23	2800	64,000	P
CONTRACT ENGINEER						
OFFICE ENGINEER	1		20	2000	40,000	–
COST ENGINEER						
TUNNEL ENGINEER						
DRAFTSMAN/CLERK						
FIELD ENGINEER	1		15	2300	35,000	P
PARTY CHIEF						
INSTRUMENT MAN	1		15	2200	33,000	–
RODMAN						
SAFETY ENGINEER	1		18	2200	40,000	P
FIRST AID MEN/NURSES	3	15	45	1200	54,000	–
TOTAL ENGINEERING			136		266,000	3
OFFICE						
OFFICE MANAGER	1		24	2000	48,000	P
PURCHASING AGENT	1		17	1500	26,000	–
ACCOUNTANT						
PAYMASTER	1		18	1200	22,000	–
TIMEKEEPER						
CLERK						
TYPIST	1		16	800	13,000	–
EEO/LABOR RELATIONS						
WAREHOUSEMEN	1		16	1800	29,000	–
GUARDS & WATCHMEN	1		17	1500	25,000	–
JANITOR/DRYHOUSEMEN	1		9	1500	14,000	–
TOTAL OFFICE			117		177,000	1

INDIRECT COST OVERHEAD LABOR PAGE 29

FIGURE B-6a. COMPUTATION SHEET

PROJECT H & N BCNT ESTIMATOR DES DATE JUL 13 1977 JUN 13 1977 I 04

DESCRIPTION	UNITS	COST PER UNIT	COST
SUPPLIES			
OFFICE SUPPLIES	24 mo	1000	24,000
ENGINEERING SUPPLIES	20 mo	600	12,000
SAFETY & FIRST AID SUPPLIES	18 mo	800	14,000
PROTECTIVE CLOTHING			DIRECT COST
EXPENDABLE ELECTRICAL SUPPLIES			DIRECT COST
SMALL TOOLS & SUPPLIES			DIRECT COST
FACILITY MAINTENANCE SUPPLIES	20 mo	500	10,000
TOTAL SUPPLIES			60,000
SERVICES			
AUDIT			25,000
CONSULTANTS			–
CIM			–
HEAT 5,000 SF	2 YR	7,000	14,000
HOME OFFICE CHARGE	24 mo	4,000	96,000
LEGAL			30,000
LIGHTING ①	730,000	.06	44,000
PHOTOGRAPHY			3,000
POSTAGE	24 mo	500	12,000
TELEPHONE	24 mo	1000	24,000
WATER, CHLORINE & ICE	24 mo	400	10,000
PHYSICAL EXAMS	30	40	1,000
TOTAL SERVICES			259,000
FEES			
DONATIONS			3,000
DUES			4,000
LICENSES, AUTOMOTIVE			2,000
LICENSES, OTHER			–
PERMITS			1,000
TOTAL FEES			10,000

DESCRIPTION	UNITS	COST PER UNIT	COST
MISCELLANEOUS			
APARTMENT RENTAL			–
OFFICE RENTAL			2,000
YARD RENTAL			–
ENTERTAINMENT			10,000
GROUP PARTIES			10,000
TRAVEL			20,000
RECRUITING & EMPLOYMENT			–
MISCELLANEOUS			5,000
TOTAL MISCELLANEOUS			47,000
TOTAL MISCELLANEOUS JOB EXPENSE			376,000

① LIGHTING KWH
100 W BULBS AT 15' C-C = 1300 ea × 24 HR × 8 mo × 26 DAYS ÷ 1000 = 650,000
SHAFT & PLANT. AREA = 15 KW × 17 mo × 26 D × 12 H = 80,000
730,000

INDIRECT COST MISCELLANEOUS JOB EXPENSE PAGE 30

FIGURE B-6b. COMPUTATION SHEET

H & N BCNT   PES   JUL 13 1977

I 05

DESCRIPTION	COST
Contract Amount = $ 12,000,000	
INSURANCE	
AUTOMOTIVE 7 ea × 2 YR × $300/YR	4,000
BUILDERS RISK .10/100/YR × CA × 2½ YR	30,000
CONTRACTURAL LIABILITY $1.50/100 × CA	180,000
EQUIPMENT TRANSPORTATION (MOVE)	27,000
FIDELITY & FORGERY	1,000
PLANT & EQUIPMENT (1) × 3.50/100/YR × 2 YR	27,000
MEDICAL INSURANCE FOR SUPERVISORY PERSONNEL	
348 MAN-MO × $100	35,000
TOTAL INSURANCE	304,000
TAXES	
GROSS RECEIPTS	
HIGHWAY USE	
INVENTORY	
PLANT & EQUIPMENT (1) × 25% × 100/100/YR × 2 YR	13,000
SALES TAX 5% (2)	257,000
TOTAL TAXES	270,000
BONDS	
PERFORMANCE BOND	
MAINTENANCE	
SUBCONTRACTOR	
TOTAL BONDS	

BOND CALCULATION

ESTIMATED BID AMOUNT ________

FIRST	$ 100,000 @	$10.00/$1000	= ________
NEXT	2,400,000	6.50 "	= ________
NEXT	2,500,000	5.25 "	= ________
NEXT	2,500,000	5.00 "	= ________
BALANCE		4.70 "	= ________
SUBTOTAL			________
SURCHARGE $	x.01 x	MO	= ________
TOTAL BOND			________

NOTES

(1) Plant & Equipment Average Value

Purchase Cost	$ 3,613,000
Salvage	+ 1,738,000
Total	5,351,000 x.5= 2,676,000

(2) Sales Tax Base

Direct Cost	Parts	$ 451,500
	Supplies	896,200
Plant & Equip	Purchases	3,613,000
	Other	129,000
Indirect	Supplies	60,000
TOTAL		$ 5,149,700

OTHER THAN MATERIALS HANDLING INDIRECT COST   INSURANCE AND TAXES   PAGE 31

FIGURE B-6c. COMPUTATION SHEET

H & N BCNT   PES   JUL 13 1977   I 05

DESCRIPTION Contract Amount = $	COST
INSURANCE	
AUTOMOTIVE	—
BUILDERS RISK	—
CONTRACTURAL LIABILITY	—
EQUIPMENT TRANSPORTATION	—
FIDELITY & FORGERY	—
PLANT & EQUIPMENT (1) × 3.50/100/YR × 2YR	12,000
MEDICAL INSURANCE FOR SUPERVISORY PERSONNEL	—
TOTAL INSURANCE	12,000
TAXES	
GROSS RECEIPTS	—
HIGHWAY USE	—
INVENTORY	—
PLANT & EQUIPMENT (1) × 1.00/100/YR × 25% × 2YR	6,000
SALES TAX 5% (2)	95,000
TOTAL TAXES	101,000
BONDS	
PERFORMANCE BOND	
MAINTENANCE	
SUBCONTRACTOR	
TOTAL BONDS	

BOND CALCULATION

ESTIMATED BID AMOUNT			
FIRST $ 100,000	@ $10.00/$1000	=	
NEXT 2,400,000	6.50 "	=	
NEXT 2,500,000	5.25 "	=	
NEXT 2,500,000	5.00 "	=	
BALANCE	4.70 "	=	
SUBTOTAL			
SURCHARGE $	x.01 x	MO =	
TOTAL BOND			

NOTES

(1) Plant & Equipment Average Value

Purchase Cost	$ 1,617,000
Salvage	+ 764,000
Total	2,381,000 x.5 = 1,190,000

(2) Sales Tax Base

Direct Cost	Parts	$ 168,900
	Supplies	86,100
Plant & Equip	Purchases	1,617,000
	Other	30,000
Indirect	Supplies	—
TOTAL		$ 1,902,000

MATERIALS HANDLING   INDIRECT COST   INSURANCE AND TAXES   PAGE 32

FIGURE B-6d. COMPUTATION SHEET

APPENDIX B

INTERVIEW PARTICIPANTS

Aghazudeh, Kioumars	Tunnel Manager Horn Construction Co. 6110 Executive Blvd Rockville, MD 20852
Altman, Donald C.	General Manager Serpentix Conveyor Corporation 1550 South Peal Street Denver, CO 80210
Anderson, Hayden	Project Manager Fruin Colnon Corporation 4805 N. Lane P.O. Box 5786 Bethesda, MD 20014
Atherton, Buck	Vice President J. F. Shea Construction Company 4720 Montgomery Lane Bethesda, MD 20014
Barth, Gary	G. B. Enterprises 42 South Holman Way Golden, CO 80401
Beerkircher, Gary D.	Product Manager, Hoists Rexnord P.O. Box 383 Milwaukee, WI 53201
Boisen, Brad	Vice President Terrametrics 16027 West 5th Avenue Golden, CO 80401
Brown, Scott L.	Manager Marine Sales Stephens-Adamson, Inc. Ridgeway Avenue Aurora, IL 60507
Brown, William F.	Sr. Sales Application Engineer Rexnord P.O. Box 383 Milwaukee, WI 53201
Butler, Gilbert	UMTA 2100 Second Street, S.W. Washingon, DC 20590

Cox, Kenneth C.	Civil Engineer U.S. Bureau of Mines 4800 Forbes Avenue Pittsburgh, PA 15213
Dagnall, C. R.	Manager Bucyrus-Erie Company P.O. Box 56 South Milwaukee, WI 53172
Dahmen, Neil	Sales Engineer The Robbins Company 650 S. Orcas Street Seattle, WA 98108
Durham, Robert E.	Regional Manager Stephens-Adamson, Inc. 5132 N. Walnut Grove San Gabriel, CA 91776
Elliot, Walter	Consultant 12090 W. 18th Drive Lakewood, CO 80215
Faddick, Robert R.	Associate Professor Basic Engineering Department Colorado School of Mines Golden, CO 80401
Fenner, R. R.	District Manager Joy Manufacturing Co. 4985 Colorado Blvd. Denver, CO 80216
Goodwin, Dan	James McHugh Construction Co. 5540 Wisconsin Avenue, N.W. Chevy Chase, MD 20014
Grant, Elton	Project Manager Clevcon (S&M) Construction P.O. Box 1292 Rochester, NY 14601
Gumz, William H.	Product Manager Rexnord 4701 West Greenfield Avenue Milwaukee, WI 53214
Heilbron, H. M., Jr.	Project Manager Granite-Groves 6603 Central Avenue Seat Pleasant, MD 20027

Hendricks, Robert S.	Vice President J.S. Redpath Limited Casa Grande, AZ 85222
Jones, Robert	Haulage Superintendent Henderson Mine Empire, CO 80438
Kenzie, J. D.	Project Manager S&M Construction Co. Rosslyn, VA 22209
Knight, Gail B.	S. A. Healy Company 1845 Market Street Camp Hill, PA 17011
Lehman, Richard	Chief Engineer J. F. Shea Construction Co. Walnut, CA 91789
Lundstedt, Tom	Sales Engineer The Robbins Company 650 S. Orcas Street Seattle, WA 98108
Malina, George	Project Manager Healy-Ball-Greenfield Washington, DC
Martin, James M.	Basic Engineering Department Colorado School of Mines Golden, CO 80401
Martin, Tom	Senior Engineer J. F. Shea Construction Company 4720 Montgomery Lane Bethesda, MD 20014
Mayo, Robert S.	Consultant P.O. Box 1413 Lancaster, PA 17604
McFarland, Russel K.	UMTA 2100 Second Street, S.W. Washington, DC 20590
Mixon, E. O.	Project Manager Kenney Construction Co. 7555 McCormick, Blvd. Skokie, IL 60076

Moore, Edward	General Manager York Canyon Mine Kaiser Steel Corporation P.O. Box 1107 Raton, NM 87740
Moran, Ray D.	President Moran Engineering Sales Co. 825 W. Washington Blvd. Montebello, CA 90640
Musso, Alfred	686 W. California Pasadena, CA 91105
Murphy, Eugene G.	Project Manager J. F. Shea Company P.O. Box 1739 Parker, AZ 85344
Nasiatka, Thomas M.	Staff Engineer Bureau of Mines 2401 "E" Street, N.W. Washington, DC 20241
Paulson, Ray	Project Manager Peter Kiewit Sons P.O. Box 248 Georgetown, CO 80444
Pelitier, Leo	Master Mechanic Morrison-Knudsen 1725 "K" Street N.W. Washington, DC 31101
Pinkerton, Dale	President Polaris Crane & Equipment Company 5445 Dahlia Commerce City, CO 80022
Provost, Allan G.	Vice President Harrison Western Corporation 1208 Quail Street Denver, CO 80215
Salmon, John	Project Manager S. A. Healy Company Box 11 McCook, IL 60525
Sanderson, Gerald D.	Product Manager Box 5900 Franklin Street Belleville, Ontario Canada K8N 5C8

Savage, Loren	Tunnel Division Manager Harrison Western Corporation 1208 Quail Street Denver, CO 80225
Schroeder, Carl T.	Marketing Manager Rexnord P.O. Box 383 Milwaukee, WI 53201
Scott, Gale G.	Manager of Marketing Box 5900, Franklin Street Belleville, Ontario Canada K8N 5C8
Tanner, E. J.	District Manager Long-Airdox Company Finleyville, PA
Tierney, Michael P.	710 Miller Court Denver, CO 80215
Torre, D. C.	Vice President Long-Airdox Company P.O. Box 331 Oak Hill, WV 25901
Traylor, Glen	Vice President Traylor Bros., Inc. P.O. Box 5165 Evansville, IN 47715
Tufaro, Steve	Project Engineer S. A. Healy Company Box 11 McCook, IL 60525
Van Lingen, Edward	Manufacturing Manager Serpentix Conveyor Corporation 1550 South Pearl Street Denver, CO 80210
Wawzyniak, David	Project Manager James McHugh Construction Co. 666 E. Rand Road Mt. Prospect, IL 60056
Wenger, William	Project Engineer S&M Construction Co. Rosslyn, VA 22209

Wightman, W. D. Toby	Vice President Underground Technology Development Corp. 8425 Frye Road Alexandria, VA 22309
Wilhelm, George	Assistant General Manager Hecla Mining Company Casa Grande, AZ 85222
Williams, George	Manager Fruin Colnon Corporation 4805 North Lane P.O. Box 5786 Bethesda, MD 20014
Zick, Paul	Project Engineer J. F. Shea Company P.O. Box 1739 Parker, AZ 85344

APPENDIX C

REPORT OF NEW TECHNOLOGY

The findings of this contract as reported herein, are primarily based upon the utilization of commercial materials handling equipment.

The purpose of this study is a state-of-the-art of materials handling in tunneling as well as developing a cost estimation model based upon techniques using various materials handling systems. The basic technology of the conventional haulage systems such as rail, crane, and hoist, was determined to be fairly adequate, however, this report identifies fifty-five problems for potential research and development programs. The emphasis of these programs are the lifting of muck by continuous mechanical methods and the horizontal transport of muck by upgraded rail haulage. Other areas of research are the investigation of belt conveyance based on recently developed belt technology and to monitor and assess the ongoing development for pipeline systems.

Through proper evaluation of alternative methods of materials handling systems applied to modern tunneling technology in the urban environment, the increasing economics factors of tunnel construction can be minimized.

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